AD-A256 407

AD

TECHNICAL report

DTIC
ELECTE
OCT 14 1992
S A

M113 Electric Land Drive Demonstration Project

Volume 1: Vehicle Systems Design and Integration

by
**Thomas R. Childers**
Gerald Sullivan
Cam-Nhung Coyne
Mark Matthews

Report Date
August 1992

92-26956

Belvoir RD&E Center

United States Army
Belvoir Research, Development and Engineering Center
Fort Belvoir, Virginia 22060-5606

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE August 1992	3. REPORT TYPE AND DATES COVERED Final 1984 to 1990	

4. TITLE AND SUBTITLE M113 Electric Land Drive Demonstration Project Volume 1: Vehicle Systems Design and Integration (U)	5. FUNDING NUMBERS 62131 M
6. AUTHOR(S) Thomas R. Childers, Gerald Sullivan, Cam-Nhung Coyne, and Mark Matthews	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Belvoir Research, Development & Engineering Center ATTN: SATBE-FGE Fort Belvoir, VA 22060-5606	8. PERFORMING ORGANIZATION REPORT NUMBER 2507

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) David Taylor Research Center ATTN: MCPO, Code 1240 Bethesda, MD 20084-5000	10. SPONSORING/MONITORING AGENCY REPORT NUMBER C 3157

11. SUPPLEMENTARY NOTES POC: Mr. Thomas Childers, 703/704-3371	

12a. DISTRIBUTION/AVAILABILITY STATEMENT Distribution unlimited; approved for public release.	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The design, construction, and integration of a computer controlled dc electric transmission in a 300 hp, 14 ton, M113 vehicle are described. The electric transmission was designed and built using off-the-shelf components: Bendix 12,000 r/min aircraft ac generators, rectifiers, Mawdsley 5,400 r/min dc traction motors, pulse width modulation motor field current controllers, and FMC two speed final drives.

14. SUBJECT TERMS Tracked vehicles, test beds, drive-by-wire, electric drive, microcomputer control	15. NUMBER OF PAGES 137
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

M113 Electric Land Drive Demonstration Project

Volume 1:
Vehicle Systems Design & Integration

by
Thomas R. Childers
Gerald Sullivan
Cam-Nhung Coyne
Mark Matthews

US Army Belvoir RD&E Center
Fort Belvoir, Virginia 22060-5606

August 1992

Table of Contents

FIGURES

Executive Summary

PROJECT PURPOSE

The objective of this project was to design, build, and demonstrate an electric drive system, including computer control, in a representative tracked vehicle. The M113 Armored Personnel Carrier (APC) vehicle was chosen to provide the test bed for demonstration and operational evaluation of the computer controlled electric transmission concept.

DESIGN GOALS

The design goals for the Electric Land Drive Demonstration project included:

- Rear drive capability

- Acceleration: 0 to 20 mph in 6 seconds
  0 to 40 mph in 45 seconds

- Gradability requirements: 60% longitudinal, 40% transverse

- Sprocket torque: 8,500 foot-lbs per side

- Steering: Fully variable, fully regenerative; able to perform spin turn at low speed

- Tractive effort to weight ratio of 0.89

- Efficiency: 200+ sprocket horsepower available over 90% of the speed torque range; fuel efficiency optimized by control algorithms

- Transparent control to driver

- Demonstrable reliability and maintainability of electric components

DESIGN OVERVIEW

In order to meet the above goals and specifications, the following design outline was chosen:

- The drive sprockets were moved from the front of the vehicle to the rear.

- The power from the 300 hp diesel engine is delivered into a gearbox which has four outputs. Two of the outputs drive the two 150 kVA ac generators which provide the electrical power needed to drive the tracks. The third output drives a dc generator which provides power for the various vehicle control circuits. The fourth output drives a stack of oil pumps which provide the cooling and lubrication for the gearbox and generators.

- The power from the ac generators is rectified and delivered to the two dc traction motors (one for each track). There is a right angle, two-speed final drive gearbox assembly between each traction motor and its respective track drive sprocket. The final drive gearboxes include a neutral, low, and high gear, plus mechanical braking.

- The coordination and control of all these and other systems are provided by a digital computer. The computer scans the drivers input, and then controls all of the vehicle systems to provide the performance requested by the driver using the control software. The status of the various vehicle systems is continually updated every 120 milliseconds (ms) by the computer so as to provide smooth operation.

Data from all of the various vehicle systems is recorded by the computer onto magnetic tape during tests for later analysis and evaluation.

The design team for the Electric Drive demonstrator consisted of BRDEC with Southwest Research Institute (SwRI) as the control system contractor. The responsibilities of the design team were:

- Belvoir RD&E Center (BRDEC):

    — Overall project responsibility.
    — Electric drive system design, control system design, test and evaluation.
    — Control system/electric drive interaction (Mr. Ellis Hitt, consultant).
    — Electrical machinery analysis (Dr. Frederick Brockhurst, consultant).

- SwRI:

    — Computer/data acquisition hardware.
    — Control software.

- BRDEC and SwRI:

    — Control software integration

Preface

This report is Volume 1 of two volumes that document the effort on the M113 dc Electric Land Drive Demonstration project for the US Marine Corps (USMC) Programs Office of David Taylor Research Center (DTRC). Volume 1 presents an overview and relates all technical efforts of the project. It provides descriptions of system components, a description of the electrical design, an overall description of the control system function, discussions of the system hardware and control software integration, conclusions and recommendations for future electric drive development. The second volume will include various studies on vehicle control systems, hazard analyses, component purchase descriptions, vehicle operating and maintenance procedures, and other related reports and documentation. The second volume should be available by July 1993. In addition, the final report from SwRI documents the control system software and computer hardware efforts performed under contract number DAAK70-85-C-0035. This report, published in two volumes in May 1990 is entitled, "Development of a Microcomputer Control System for a 300-HP Electric Drive Vehicle." Volume 1 is entitled, "Control System Description" and Volume 2 is entitled, "Electrical Wiring Information." Requests for copies of these reports should be sent to: Defense Technical Information Center, Cameron Station, ATTN: DTIC-FDAC, Alexandria, VA 22304-6145. The M113 dc Electric Land Drive Demonstration is one facet of the USMC's larger R&D effort to develop the necessary technologies that are required for the system development of the Advanced Amphibian Assault (AAA) Vehicle.

It is worthwhile to discuss the relationship of this effort to an earlier DTRC competitive solicitation for the development of an electric drive train. During 1982, the Marine Corps Programs Office released a competitive Request for Proposal (RFP) for an exploratory development effort to design, fabricate, install, and test an electric drive train in an M113 test bed vehicle. All responsive offerors proposed ac drive systems using advanced high speed ac motors. A decision not to award was made on the basis of cost, but significant technical concerns in all cases were the required volume, weight, and complexity of the power control electronics (ac-dc-ac converters). The subsequent Belvoir concept for a dc drive system was pursued because of the advantages in cost, simplicity, weight, and reduced power electronics requirements. However, the power electronics for ac drive are smaller and better now than they were in 1982, making today's ac drive a more serious competitor for the dc drive.

Acknowledgements

Section I
Vehicle System Description

VEHICLE COMPONENTS

This section describes and discusses the following major components of the Electric L?
Drive vehicle (see **Figure 1**). An illustration of the vehicle drive system is presented in
Figure 2.

- M113 APC Chassis
- 300 hp diesel engine
- Westech gearbox
- (Two) 150 kVA, 120/208 V, 12,000 revolutions per minute (r/min) generators
- Solid state rectification with interphase transformer
- dc brushless 28 V, 650 A generator
- dc traction drive motors
- dc bus between motors for regenerative steering
- Oil-cooled braking grid
- ac generator field current controller
- dc motor field current controller
- Digital control system
- dc motor adapter gears
- Two speed final drives with modulated braking

M113 APC Chassis. The vehicle chosen as an appropriate test bed for the Electric Drive
Demonstration project is an M113 APC manufactured by FMC Corporation Ordnance
Division of San Jose, CA. The vehicle's National Stock Number (NSN) is 2350-01-068-
4077; identification number, 23333.

Engine. The source of power for the vehicle is a Detroit Diesel model 6V-53T turbocharged
diesel engine producing 300 Bhp at 2,900 r/min and weighing 1,695 pounds. The engine
consumes fuel at a rate of 121.4 pounds per hour at 2,800 r/min.

Cooling for the engine is provided by a horizontally mounted radiator with a separately
mounted hydraulic driven fan. The hydraulic flow required by the fan is supplied by the
Detroit Diesel engine. The oil sump is attached to the right rear of the vehicle. This sump
also provides MIL-L-2104 OE/HD 30W oil for the following vehicle systems:

- Final drives
- Adapter gears
- Braking resistor

300 HP DIESEL ENGINE

TWO SPEED FINAL DRIVE

150 kVA ALTERNATORS

DC GENERATOR

DC DRIVE MOTOR

OIL PUMPS
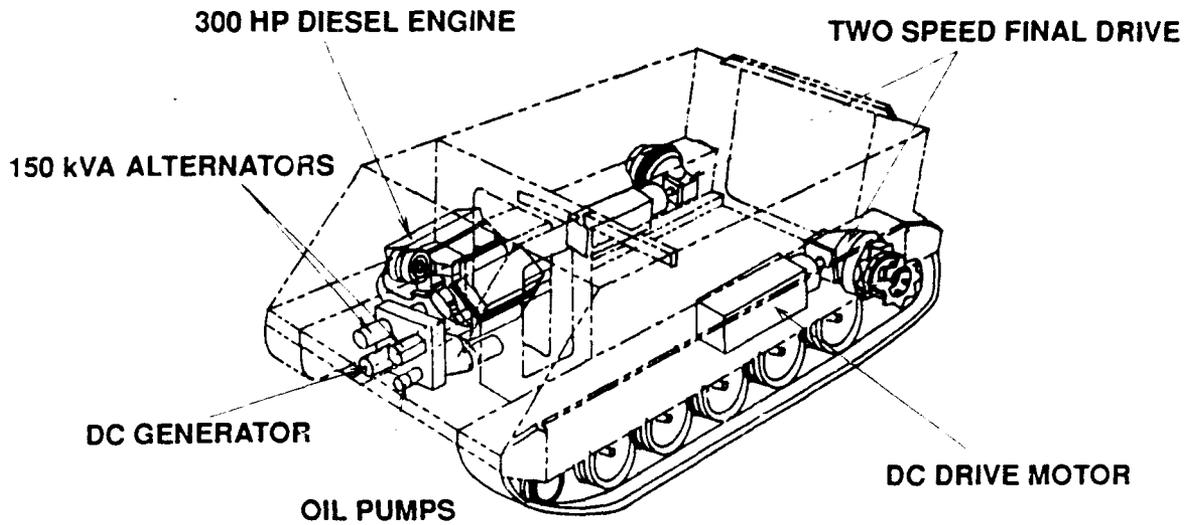
Figure 1. Major Components—M113 Electric Drive Vehicle

2 150 kVA BENDIX ALTERNATORS (Model 28B329-1)

28 VOLT BENDIX DC GENERATOR (Model 30B95-3)

BENDIX ADAPTER (Model 1549132)

GEAR, 1:4.5 FOR 28B329-1, 1:3 FOR 30B95-3

CONTROLS

ENGINE
6V-53T
300 HP

RECTIFIER

DC POWER
TO MOTORS

AC POWER
FROM ALTERNATORS

DC
MOTORS

FINAL
DRIVES

TRACKS
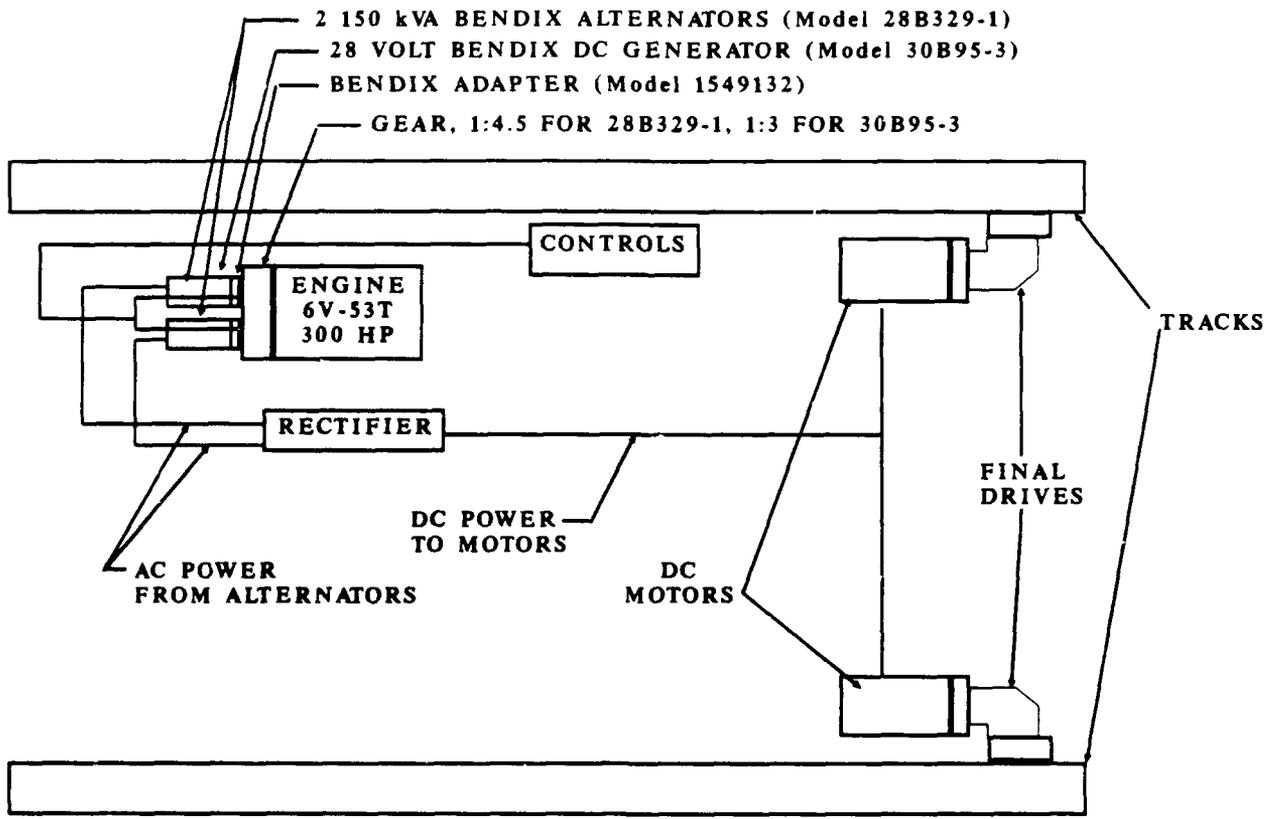
Figure 2. Concept Illustration—Power Unit and Drive System

The engine radiator and radiator fan are mounted directly above the engine in the top engine compartment cover. The fan blows air directly upward out of the engine compartment. This creates a partial vacuum in the engine compartment which causes air to be drawn into the compartment through the radiator. The engine combustion air filter is also in the engine compartment and is mounted on the front bulkhead. The muffler is located in the engine compartment on the right side; its exhaust is directed upward through an opening in the top engine compartment cover.

Servicing the engine is facilitated by having the lube filter and fuel filters remotely mounted on the front of the left engine compartment wall near the compartment access door. Draining the engine oil is accomplished through an access hole in the bottom of the engine compartment.

Westech Gear Box and Attached Components. Mounted onto the flywheel housing of the engine is a four output Westech gearbox powered by the engine output shaft through a torsional damping coupling. The gearbox is oil cooled and lubricated and has its own supply pump which draws oil from the MIL-L-23699 oil sump.

Two of the gearbox outputs drive two Bendix 150 kVA (model 28B329-1), 120/208 V, .75 pf, 400 Hz brushless generators at 12,208 r/min when the input is 2,654 r/min (1:4.6 ratio). Each generator has overload capabilities of 225 kVA for 5 minutes and 300 kVA for 5 seconds, weighs 75 pounds, and is 7.5 inches in diameter and 13.5 inches long.

The generators are oil cooled and oil lubricated. The oil is MIL-L-23699 and is supplied by pump assembly. At full speed, each generator receives about 7 gpm at 250 psi. Oil is scavenged from each generator by separate pumps which are part of the pump assembly. An adapter housing designed and built by Bendix is mounted between the ac generators and the Westech gearbox and provides a bearing to support the front of the ac generator shafts.

Also mounted onto the gearbox is a Bendix 30B95-3 oil-cooled dc generator which is rated at 28 V and 650 A. The unit has its own pump which develops an oil flow of 0 to 5 gpm, depending on the engine speed. The output voltage is controlled by a voltage regulator so that it will remain at 28 V dc over its range of operating speeds. At an engine speed of 2,800 r/min, the gearbox rotates the generator at 8,022 r/min. This gives a speed increase ratio of 1:2.87. The dc generator is brushless, self-excited, and provides the power required by the control power circuits. There is a 24 V main battery connected across the generator output. It serves to buffer the load transients and provides system start-up power.

To provide the oil flow needed by various systems, there is a Tyrone oil pump stack attached to the fourth output of the Westech gearbox. At an engine speed of 2,700 r/min, the gearbox rotates the pump stack at 1,800 r/min, providing a speed reducing ratio of 3:2.

The oil returning to the sump is cooled by the transmission oil cooler which is a part of the diesel engine. The MIL-L-23699 oil for the Westech gearbox and its attached components is drawn from the sump mounted on the left side of the vehicle. The Interphase Transformer (IT) is also cooled with MIL-L-23699 oil.

DC Traction Motors. The motors used are dc traction separately excited shunt motors. The motors are air cooled. The Mawdsley motors take electrical power from the 300 V dc bus and convert it to mechanical power for the final drives. The motors have the following parameters:

- Size: 14" by 14" by 24", square frame
- Weight: 720 pounds
- Rated speed: 5,400 r/min
- Torque: 500 ft-lbs maximum
- Volts per r/min: 0.1 at a field current of 160 A
- Ft-lb per A: 0.62 at a field current of 150 A

Detailed parameters of the Mawdsley motors are presented below:

MAWDSLEY 180XS DC MOTOR

Constraints

Armature R Hot/Cold	.024/.017 ohm
Armature L/T.C.	.9mH/37ms
Field R Hot/Cold	.205/.130 ohm
Field L/T.C.	50mH/300ms
Com. Field R 65°C/Cold	.0095/.0076 ohm
Rotor WR^2	.45kg-m^2/8 lb-ft

Losses

Armature Power, Full Field, .5 speed	5 kW
.5 Field, Full speed	2.8 kW

Thermal Limits

Armature	Cont.	430A
	2 min. Cold	800A
Field	Cont.	130A
	10 min. Cold	160A

Cooling Air

Cooling Air	400cfm at 7.2 inches water
Maximum Ambient Cooling Air	180°F

Adapter Gears. Mounted onto the drive end of each of the dc motors is an FMC adapter gearbox. The adapter gearbox decreases the input speed by a factor of 0.604 and also reverses the rotational direction of the Mawdsley motor at its output. The adapter gearbox output is connected to a universal joint (U-joint) assembly which is in turn connected to the FMC final drives. Because the vehicle is not perfectly rigid, the U-joint assembly will allow for slight movement between the dc motors and the FMC final drives.

FMC Final Drives. The final drives contain a planetary gear assembly providing neutral, low, and high gear ratios, and a clutch, shifting, and braking assembly. A reverse gear is not needed because the direction of rotation of the dc motors can be reversed as required by changing the direction of the dc motor field current. The clutch, shifting, and braking mechanisms in the final drives are all controlled hydraulically. These hydraulic flows and pressures are in turn controlled by the computer.

There are two sets of planetary gears; one has a ratio of 4.48, and the other has a ratio of 2.34. Each set has a corresponding clutch. If the low clutch is energized, the power flows from the input to the output via both gear sets and the input to output ratio becomes 10.5 to 1. If the high clutch is energized, the power flows from the input to the output via the larger planetary gear only, and the input to output ratio becomes 4.48 to 1. When neither clutch is energized, the input is not connected to the output. There is also a set of bevel gears to provide the 90 degree relationship between the input and output shafts.

The final drive brake assembly is connected to the output shaft. This assembly contains springs that keep the brakes "on" until a hydraulically operated piston overcomes the springs and releases the brake (hydraulically released, spring-applied mechanical brake). The brake assembly is oil cooled but does not run submerged in oil.

A solenoid-actuated double brake valve was added to control the brake pressure. Its action is controlled by the digital control computer with 24 V pulse width modulation (pwm) signals. A 0% duty cycle corresponds to maximum braking (0 psi) and a 100% duty cycle corresponds to minimum braking (250 psi). The brakes are activated when hydraulic pressure is lowered so that a spring assembly engages the brakes. The brakes are disengaged when increasing hydraulic pressure adds tension to the springs. A park switch was added to the gearshift lever so that when the gearshift is in PARK, this switch de-energizes a relay which interrupts any signal from the computer to the brake valve. This insures that the brakes are fully on in PARK. It is also possible for the operator to apply full brakes at anytime by depressing the brake pedal past a detent and activating a pilot valve on the brake relief valve, thereby releasing all brake pressure.

The modulated brakes in the final drives will be used only under two conditions:

- During regenerative steering, when there is not enough regeneration of power from the inside motor to the outside motor to perform the turn required by the operator, the modulated brake on the inside final drive will be activated to help slow the inside track.

- During dynamic braking conditions, when the dc motors (acting as generators) are not able to convert a sufficient amount of mechanical energy to electrical energy to slow the vehicle at the desired rate, the modulated brakes in the final drives will be activated to help slow the vehicle. The use of the modulated brakes is kept to a minimum (within safety requirements) so that the wear and tear on the braking components can be minimized.

The input speed range for the final drives is 0 to 3,000 r/min. This creates an output range of 0 to 286 r/min in low gear (a ratio of 10.5:1) and 0 to 690 r/min in high gear (a ratio of 4.35:1). The design calls for a final drive output of 690 r/min to move the vehicle at its top speed of 40 mph on a straight, level and firm surface. This requires 600 foot-lbs of torque from each final drive to overcome the rolling resistance of the vehicle on a straight, level and firm surface. However, the 40 mph top speed was not achieved in this vehicle because the final drive inefficiencies were much greater than expected.

VEHICLE MODIFICATIONS

This section describes the modifications made to the original M113 APC vehicle to accommodate the components of the electric drive system.

Engine Compartment. The original top engine compartment cover was modified to allow for the engine radiator and the cooling fan. Holes were cut into the cover so that the radiator and fan could be installed on the top of the engine compartment. The fill cap for the radiator is now on the top of the vehicle next to the driver's overhead hatch.

Two panels were cut from the right side engine compartment wall to allow easy access to the engine and control system components.

Passenger Compartment and Final Drive Housing. The original passenger benches were removed to allow room for the motors, oil pumps, oil filters, and oil lines. New passenger benches which accommodate the motors, pumps, and filters were built and installed.

The original floor was also removed to allow room for the above components. A new floor was installed to cover the areas not taken up with the motors, pumps, and filters.

Two circular housings were installed on the rear of the vehicle to contain the FMC final drive units. They were constructed of 1.5 inch aluminum which is designed to withstand shocks encountered during operation. There is a cover plate which seals the final drive from the environment during operation.

A side view drawing of one final drive housing is presented in Figure 3. A rear view drawing is presented in Figure 4.

Sumps. On each side of the rear of the vehicle is a sump for the 23699 oil mounted on the left and the 2104 oil mounted on the right. The capacity of each sump is approximately 50 gallons.

Detailed drawings of the sumps are presented in Figures 5 and 6.
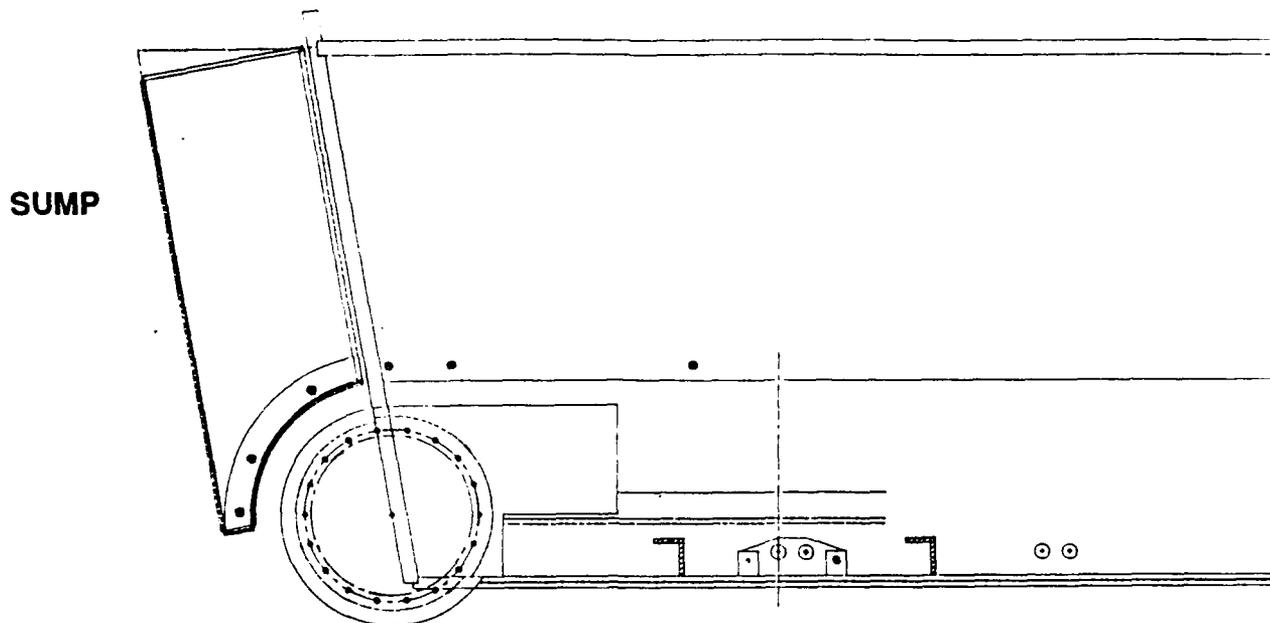
SUMP

FINAL DRIVE HOUSING

Figure 3. Final Drive Housing (Side View)

FINAL DRIVE HOUSING   FINAL DRIVE
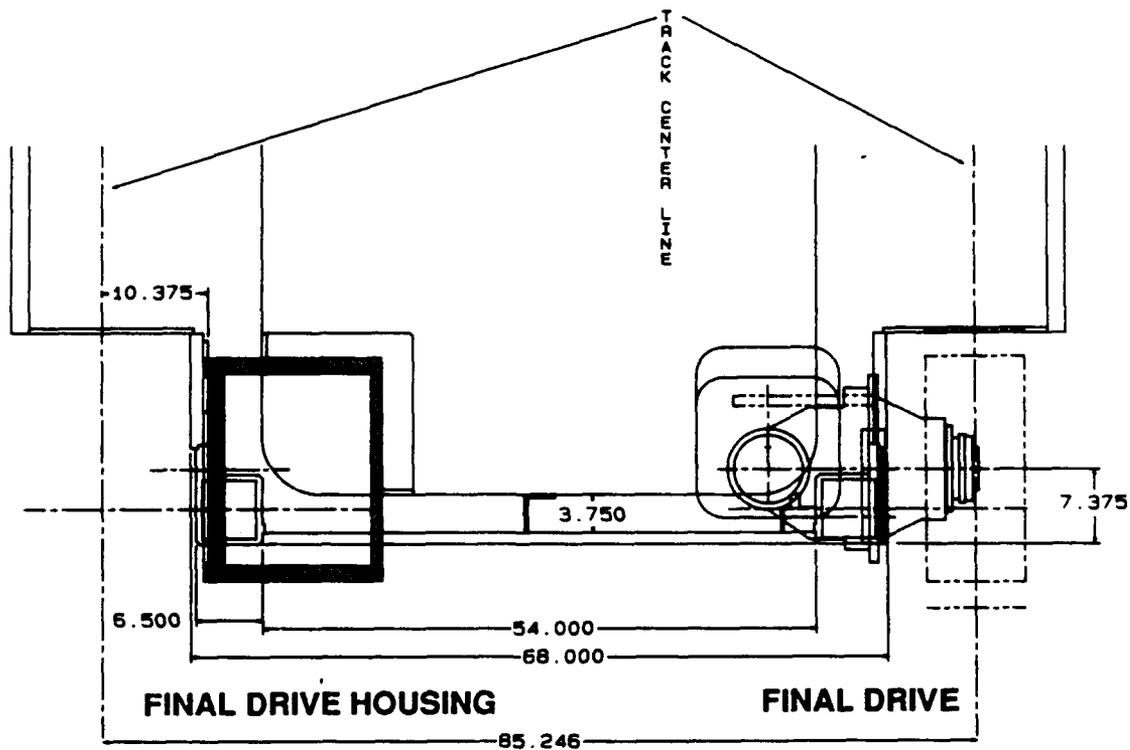
Figure 4. Final Drive Housing (Rear View)
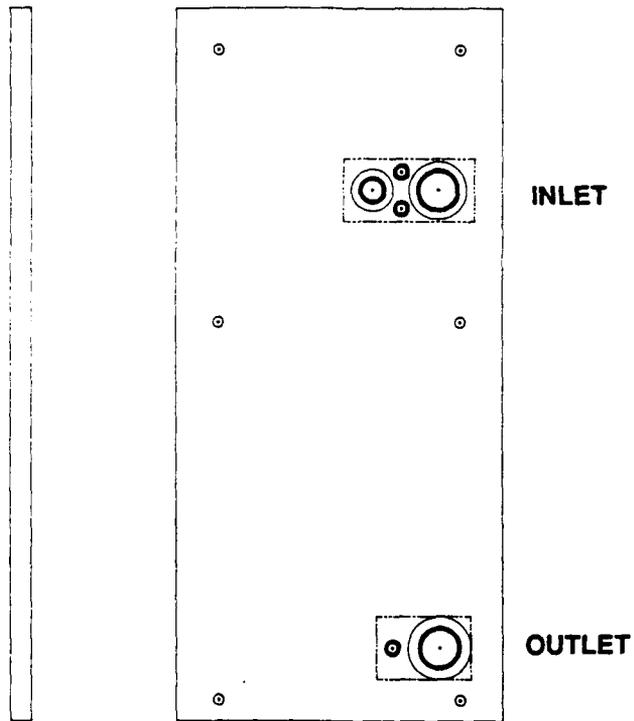
Figure 5. Front View of 23699 Oil Sump
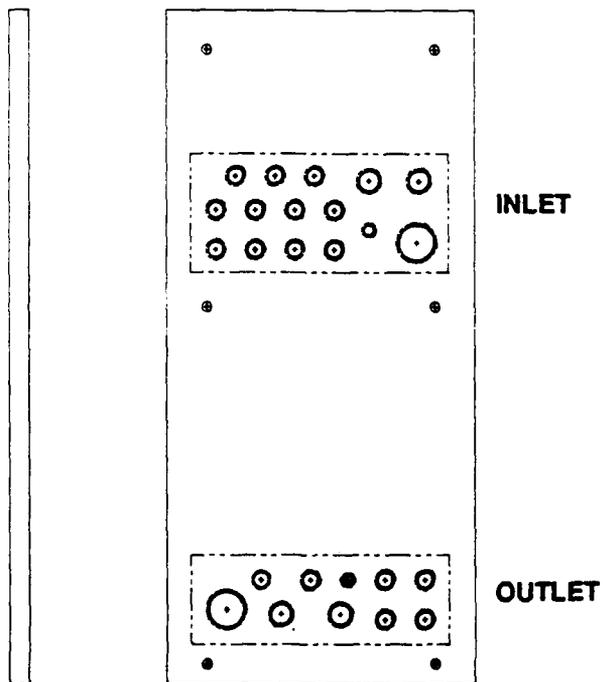
Figure 6. Front View of 2104 Oil Sump

Ramp. To make room for the final drive housings, a 16" by 16" piece was cut from the bottom corner of each side of the ramp. The gasket on the rear opening was re-routed to maintain the watertight integrity of the vehicle. The two outer hinges for the ramp were moved toward the center to make room for the final drive housings.

Front End Idler Assembly. The track idler assembly was removed and replaced by an assembly designed and constructed by BRDEC. Relocation of the assembly was necessary due to the change from front drive to rear drive, while the redesign (modeled after the M48 tank track idler assembly) attempts to accomplish an automatic track tensioner based on the location of the front road wheel. This assembly accomplishes the following tasks:

- Allows easier installation and removal of the tracks
- Provides proper tension to the tracks once installation is complete
- Compensates for excessive slack in the tracks when the front road wheel is displaced

Easier installation and removal of the tracks is accomplished by attaching the front idler wheel to a hydraulic piston tensioner. To install or remove the tracks, the fluid (grease) is drained from the piston which moves to its position of least extension. Once the tracks are installed, grease is added to the tensioner which causes the idler wheel to move forward until proper tension is put on the tracks.

When the front road wheel hits a bump or other obstacle, it is upwardly displaced such that some or most of the tension is removed from the track. To compensate for this, there is a rocker arm assembly connected to the front road wheel which causes the pivot end of the tensioner assembly to be moved forward (which causes the idler wheel to be moved forward) so that tension on the track is maintained while the front road wheel is upwardly displaced.

Detailed drawings of the front wheel tensioner assembly are presented in Figures 7 and 8.

Steering Wheel. The original lateral steering levers were replaced with an automobile type circular steering wheel. The tilt angle of this steering wheel can be adjusted to suit the driver. The adjustment of the steering wheel, when coupled with the adjustment of the driver's chair, allows the vehicle to be driven by everyone from a 5% body size female to a 95% body size male.

Brake Pedal. The original M113 vehicle did not incorporate a brake pedal because braking was done by pulling back on the lateral steering levers. The BRDEC-installed brake pedal is to the left of the accelerator pedal.
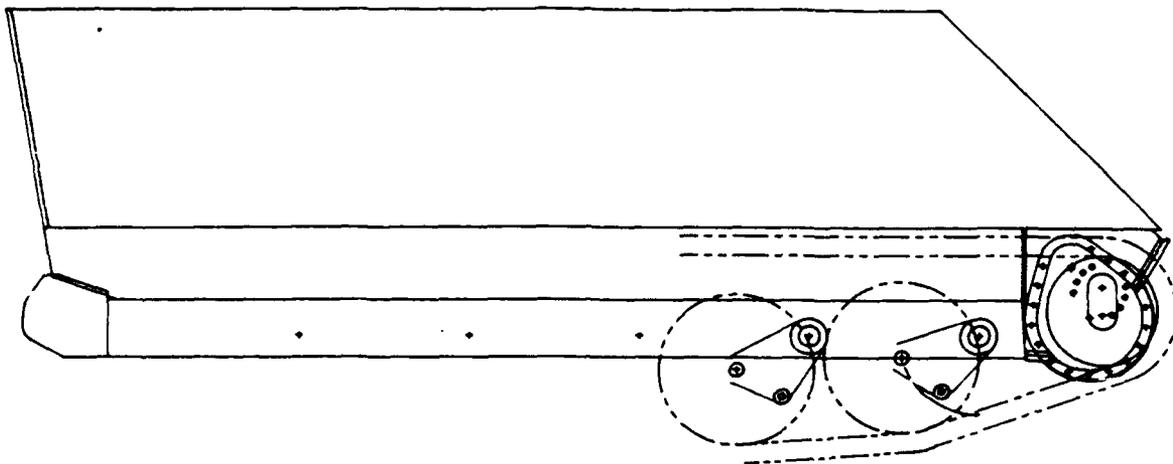
Figure 7. Tensioner Assembly
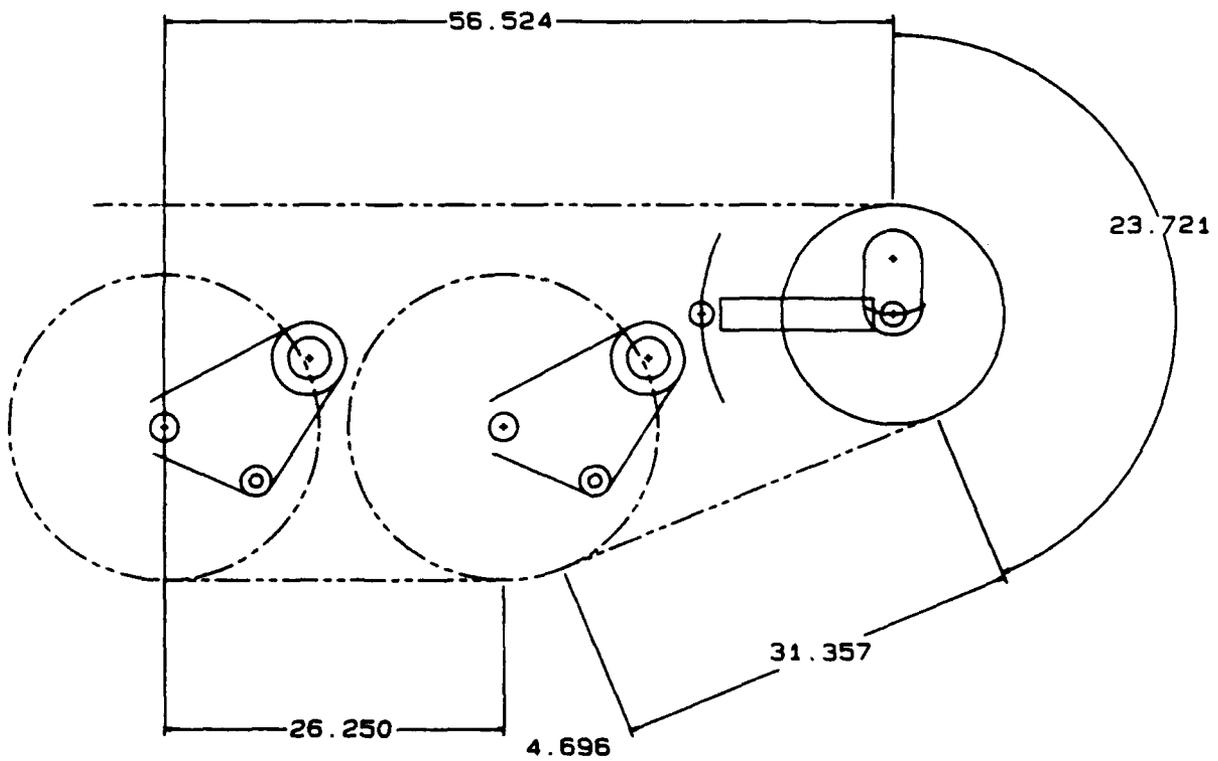
Figure 8. Tensioner Assembly—Exploded View

COMPONENT WEIGHT BREAKDOWN

COMPONENT:	WEIGHT (pounds)
Alternators	150
Alternator adapters	64
Engine gear	200
Rectifiers	68
Drive motors	1,440
Motor field supply (dc generator)	105
Controls	
Computer	20
Computer power supply	40
Computer batteries	20
Transducers	9
Cables	15
Brake pedal	4
Accelerator pedal	4
Steering assembly	10
Gearshift	3
Engine governor and activator	10
Control component boxes	75
Contactors	30
Alternator field control	10
Motor field control	10
Adapter gears	200
Final drives	608
Braking grid	25
MIL-L-23699 oil + sump	250
MIL-L-2104 oil + sump	250
Final drive pumps	100
Westech gearbox driven pumps	75
Oil to air heat exchanger	50
Hydraulic valves	50
Hydraulic hoses and fittings	60
Fan, pump, pulley, and bracket	30
Motor fans and ducts	40
Interphase transformer	25
Winch for ramp	22
Engine compartment safety plates	180
Vehicle power supply (isolation)	60
Fire suppression system	33
Total	**4,345**

Section II
Electrical System Design

A schematic of the vehicle electrical power system is presented in Figure 9.

POWER RECTIFIER

The 3-phase power from the two Bendix ac generators is connected to two 3-phase full wave bridge rectifiers connected in parallel. The rectifiers used are Westinghouse Pow-R-Briks (Model # PIZ9ADR900V) rated at 800 V and 800 A average.

DC voltage ripple is reduced by having the two generator stators displaced with respect to each other by 15 degrees. This configuration is sometimes called a 12-phase, multiple Y-delta, double way rectifier. In our application, the 30 degree phase shift in mounting the generators replaces the phase shift of the Y-delta transformer. The output of the rectifier is 300 V dc.

The rectifiers are mounted directly onto the vehicle wall and thus they have a substantial heat sink.

INTERPHASE TRANSFORMER

The positive output from each rectifier bridge is connected to one end of an interphase transformer (IT) winding and the center tap of this winding is the supply point for the load.

The purpose of the IT is to allow full parallel operation of the two rectifier bridges and provide an impedance across which a large portion of the ripple voltage is dissipated. The IT was designed and built in-house.

The IT consists of two 5" wide x 5.5' long sheets of copper wound onto a silicon steel cut core. The sheets are wound so that the currents in the two sheets flow in opposite directions. If the voltages on the two rectifiers bridges begin to diverge, the IT will bring them back into balance, i.e., back to the same value. If the current in one (or both) of the sheets begins to change, it creates a magnetic flux change that results in an induced voltage on the other winding so that neither rectifier bridge becomes reverse biased. This prevents the parallel, phase-shifted alternator-rectifier assemblies from acting as a combined 6-phase unit. Six-phase operation would result in increased losses because the phase currents would be doubled, resulting in higher rms currents even though the conduction period is halved.

The IT and the two rectifier bridge circuits are designed to be in balance at the highest power rating of the alternators. This is necessary for two reasons:
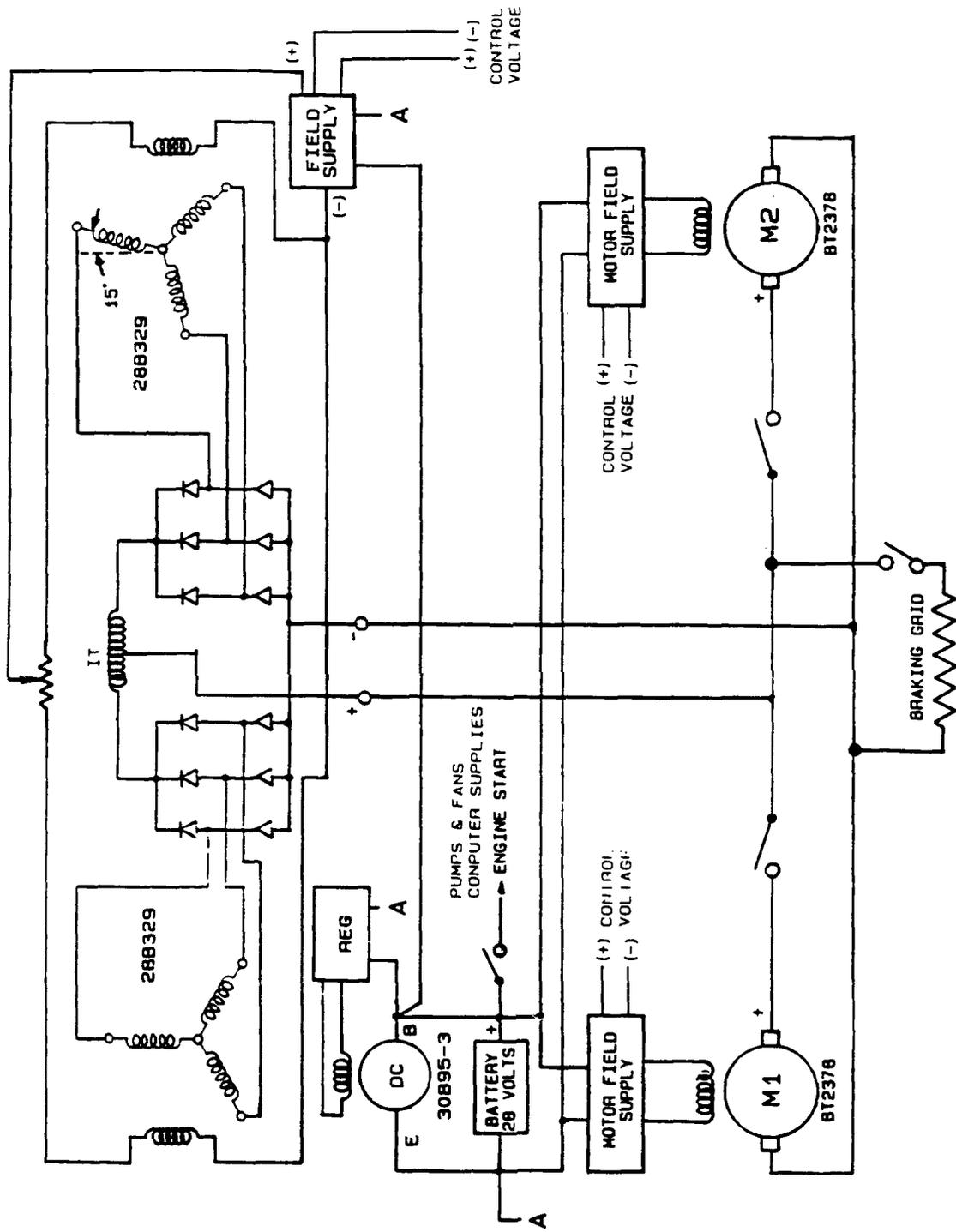
Figure 9. Vehicle Electrical Power System Schematic

- The IT core needs to be sized for the largest likely voltage difference per cycle expected to appear between the two bridges.

- To prevent either of the two rectifier bridges from carrying a disproportionately large current because this could damage the rectifier diodes. For maximum low speed torque, the alternators are allowed to operate in the twice-rated-current-for-5-seconds regime. Maximum current requires equal load current sharing.

Below the maximum power rating for the alternators, it is not critical that the two rectifier bridges be in exact balance because the power flows will be within the safe operating range of the diodes in the rectifiers.

Preliminary power assembly tests indicate that the IT does not overheat under maximum load conditions. The IT is placed in an oil sump for cooling.

The following are the voltage and current design parameters for the IT:

- The maximum rated voltage across the IT is 50 V at 900 Hz. The nominal voltage under ideal conditions is 22 V rms equivalent.

- The current rating corresponds to the combined rectifier output current ratings of the Bendix alternators:

  — 1,020 A (continuous, 100% rated)
  — 1,530 A (5 minutes, 150% rated)
  — 2,040 A (5 seconds, 200% rated)

DC POWER SYSTEM

There are four dc power systems on the vehicle:

- An isolated 650 A, 28 V system that is supplied by the Bendix dc generator in parallel with two series connected 12 V batteries.

- A grounded (connected to chassis) 28 V system that powers the vehicle lights, horn, bilge pumps, and radio and provides power to close the main dc contactor. This system gets its power from the system described above via a dc-to-dc power supply and a 24 V battery.

- An isolated 28 V system for the computer and the transducers which also gets its power from the system described above via a dc-to-dc power supply and a 24 V battery.

- A main isolated 300 V drive motor supply which is powered via the two ac generators, interphase transformer, and power rectifier.

A schematic of the 300 V dc power circuit is presented in Figure 10. Schematics of the 28 V dc power circuit are presented in Figures 11 through 13.

Figure 10. Schematic of Vehicle 300 V dc Electrical System
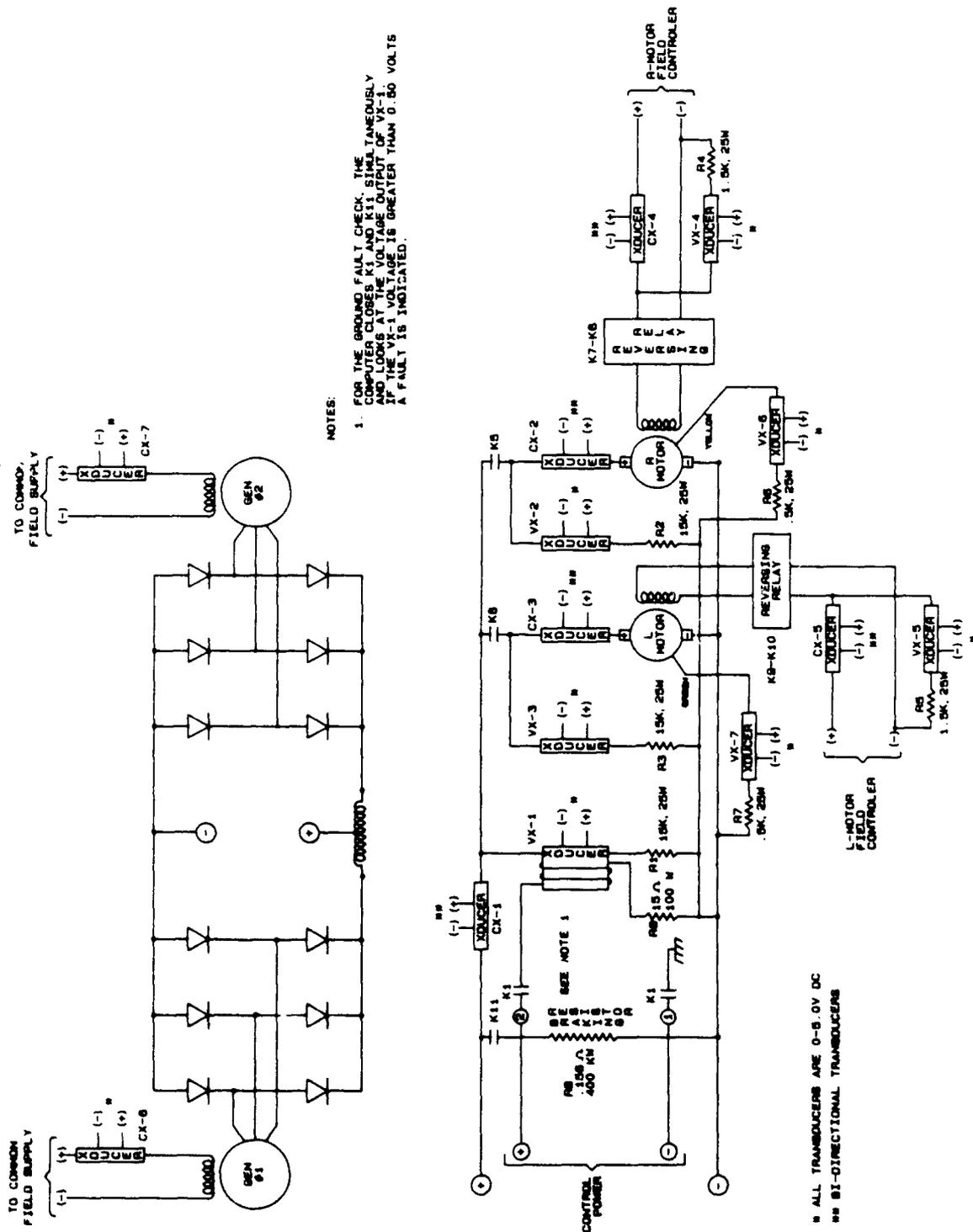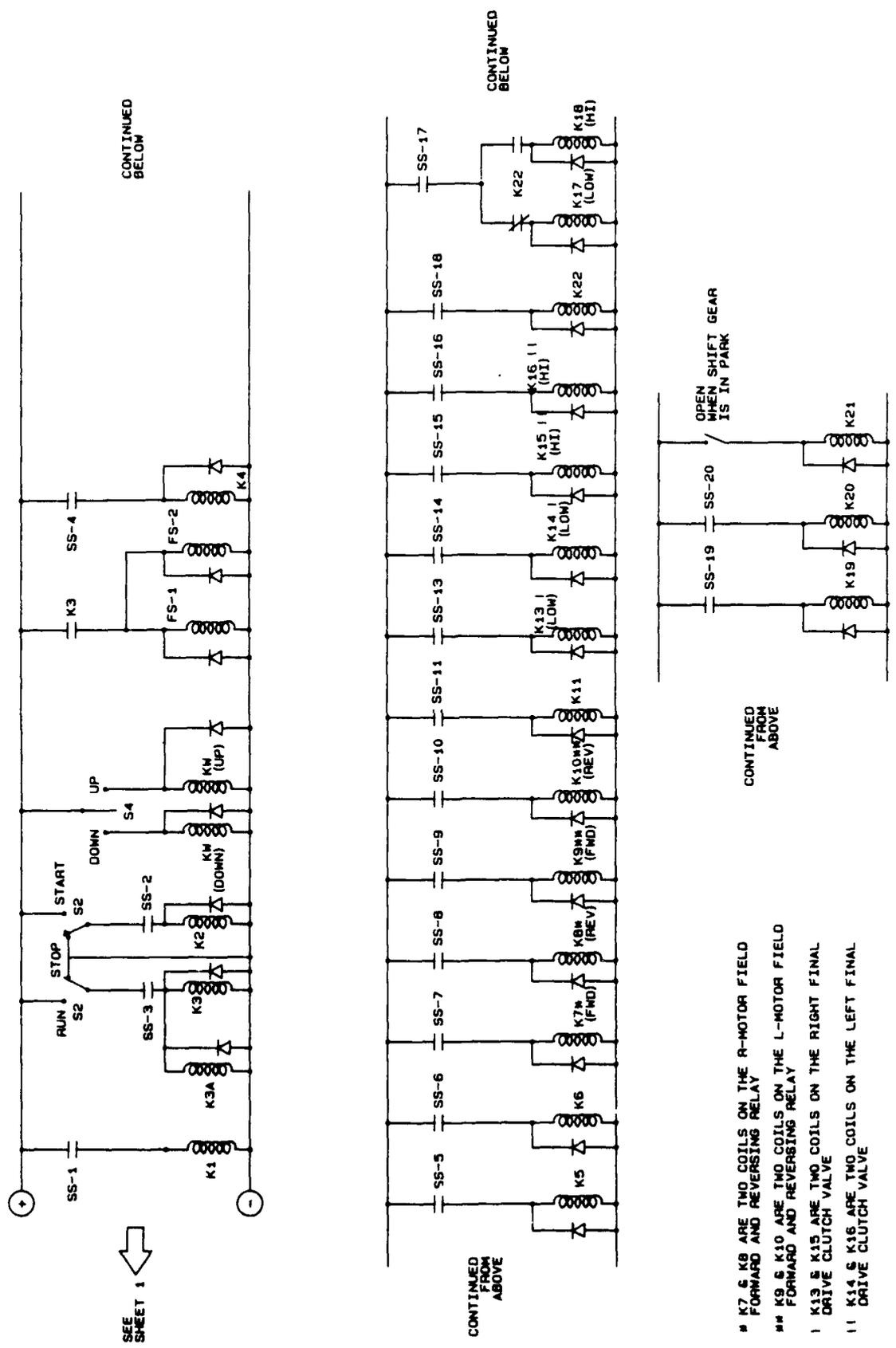
NOTES:

1. FOR THE GROUND FAULT CHECK, THE COMPUTER CLOSES K1 AND K11 SIMULTANEOUSLY AND LOOKS AT THE VOLTAGE OUTPUT OF VX-1. IF THE VX-1 VOLTAGE IS GREATER THAN 0.50 VOLTS A FAULT IS INDICATED.

* ALL TRANSDUCERS ARE 0-5.0V DC
** BI-DIRECTIONAL TRANSDUCERS

Figure 11. 28 V dc Power Circuits (sheet 1 of 2)

Figure 12. 28 V dc Power Circuits (sheet 2 of 2)
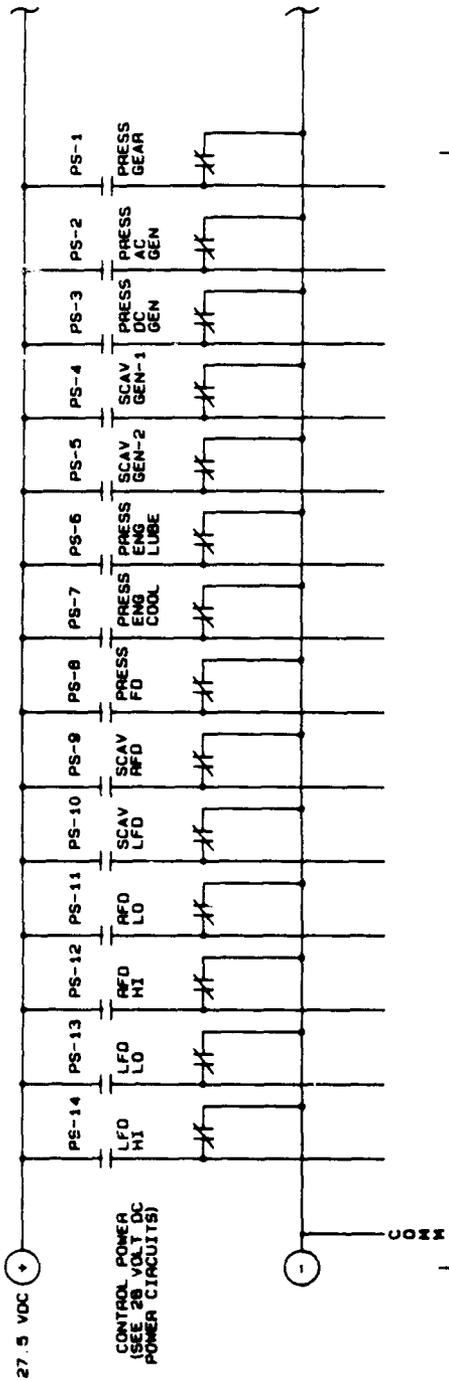
17
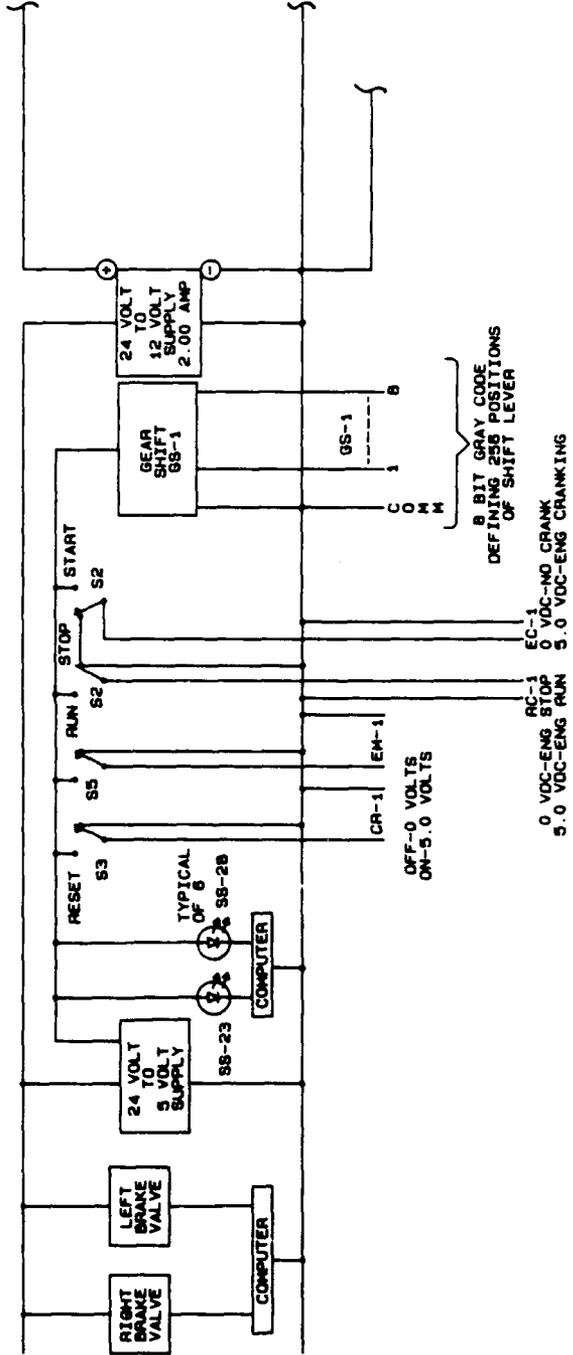
Figure 13. 28 V dc—Computer and Transducer Circuits (sheet 1 of 2)
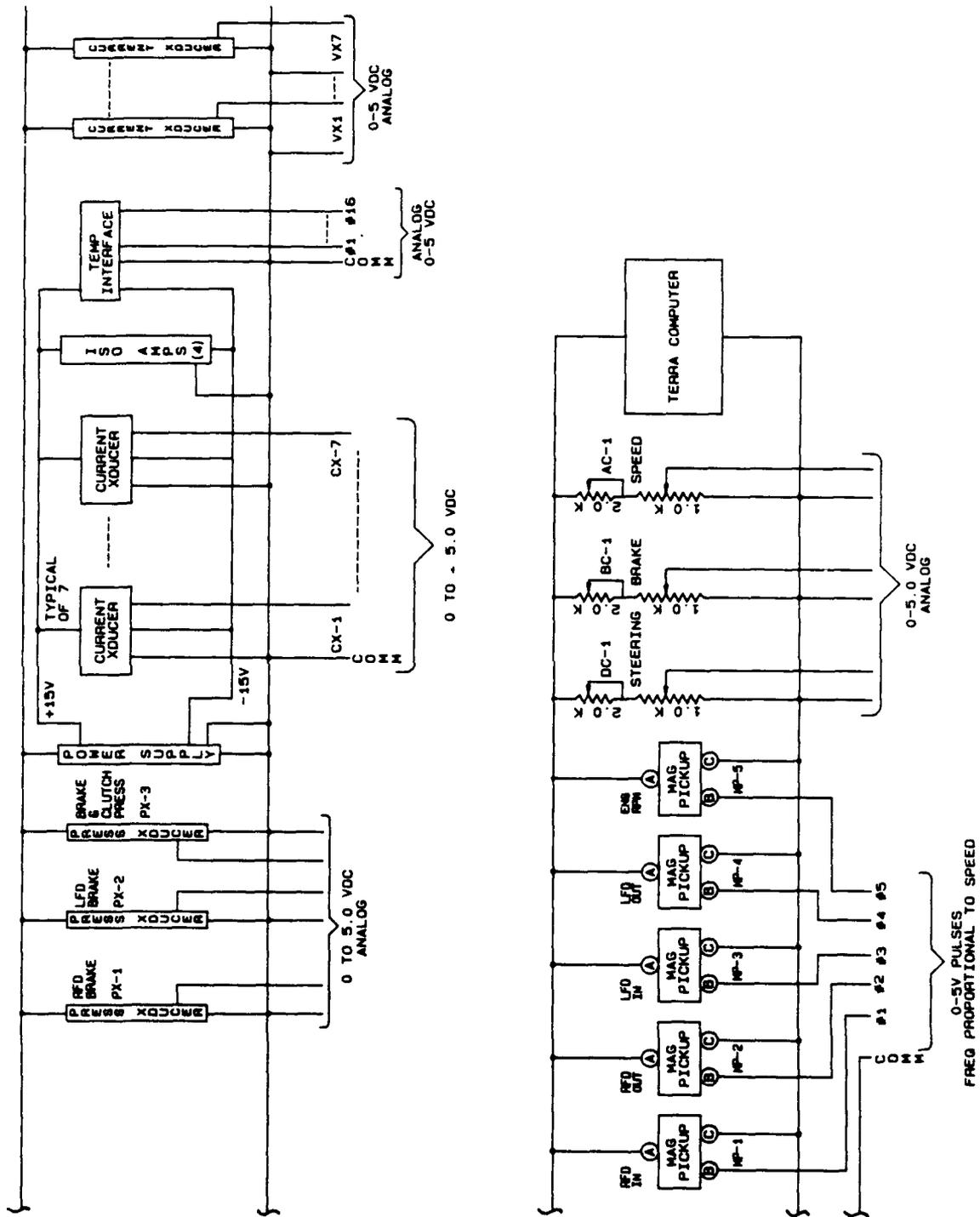
Figure 13. 28 V dc—Computer and Transducer Circuits (sheet 2 of 2)

28 V ISOLATED DC SUPPLY FOR THE COMPUTER SYSTEM

One of the requirements for proper operation of the computer system and the transducers which supply data to the computer is that the circuit connecting these systems be free from electrical transients. Transients appearing in this circuit could very possibly be interpreted by the computer as data from the transducers, thus causing the computer to output faulty information. Transients could also damage the circuitry of the transducers or computer.

The 28 V dc bus, which supplies power to the dc and ac generator fields, Mawdsley motor fields, pump motors, and starter has many transients appearing across it due to the highly variable nature of these devices. These transients make it necessary to isolate the 28 V dc computer and transducer circuit from the main 28 V dc bus.

The isolation circuit consists of a battery which is kept continually charged by the main 28 V bus through a 28 V, 12 A dc-to-dc switching power supply. This isolation circuit assures that no transients from the main 28 volt dc bus will appear in the computer or transducer circuit. Other advantages of this circuit are elimination of ground loops between the isolated circuit and the main dc bus circuit because they each have separate grounding systems, and the availability of power if the dc generator fails. The battery used to supply the isolated circuit could provide power to the computer and transducer circuits for about an hour before it needs recharging. This 28 V isolation circuit also powers three lower dc voltage output switching power supplies: 12 V for the mag pickups, (+) and (-) 15 V for the current transducers, and 5 V for the SC-1 computer.

The power supply circuit is shown in Figure 14.

BRAKING RESISTOR

The braking resistor is connected across the two motor armatures to absorb the vehicle kinetic energy in a dynamic braking condition. Kinetic energy is stored in the mass of the rotating armatures and the load which the motors are driving. This energy must be extracted to brake the motors and the load in a dynamic braking condition. The energy is extracted by first reducing the field currents of the generators to 0, and then closing the braking resistor contactor that connects the resistor across the two motors. This forces the armature currents to flow in the reverse direction; the motors then become generators. The motor generated power is dissipated as heat in the braking resistor.

The braking resistor (BR) was designed and built in-house. The BR consists of a counter-wound mesh of nichrome wire immersed in an oil filled container. The oil (2104 OE/HD 30W) is moved through the container at a flow rate of 30 gpm. At this flow rate, the power absorption capability is 4,130 Watts (W) per °C temperature rise of the oil. The mesh is wound such that half the length of the mesh carries current in the opposite direction from the other half of the mesh in adjacent cylindrical layers. This non-inductive winding arrangement eliminates the magnetic field which would normally be present with a cylindrical solenoid winding. This removes the potential for stray, field-induced upset of on-board electronics and eliminates a potential source of magnetic signature.
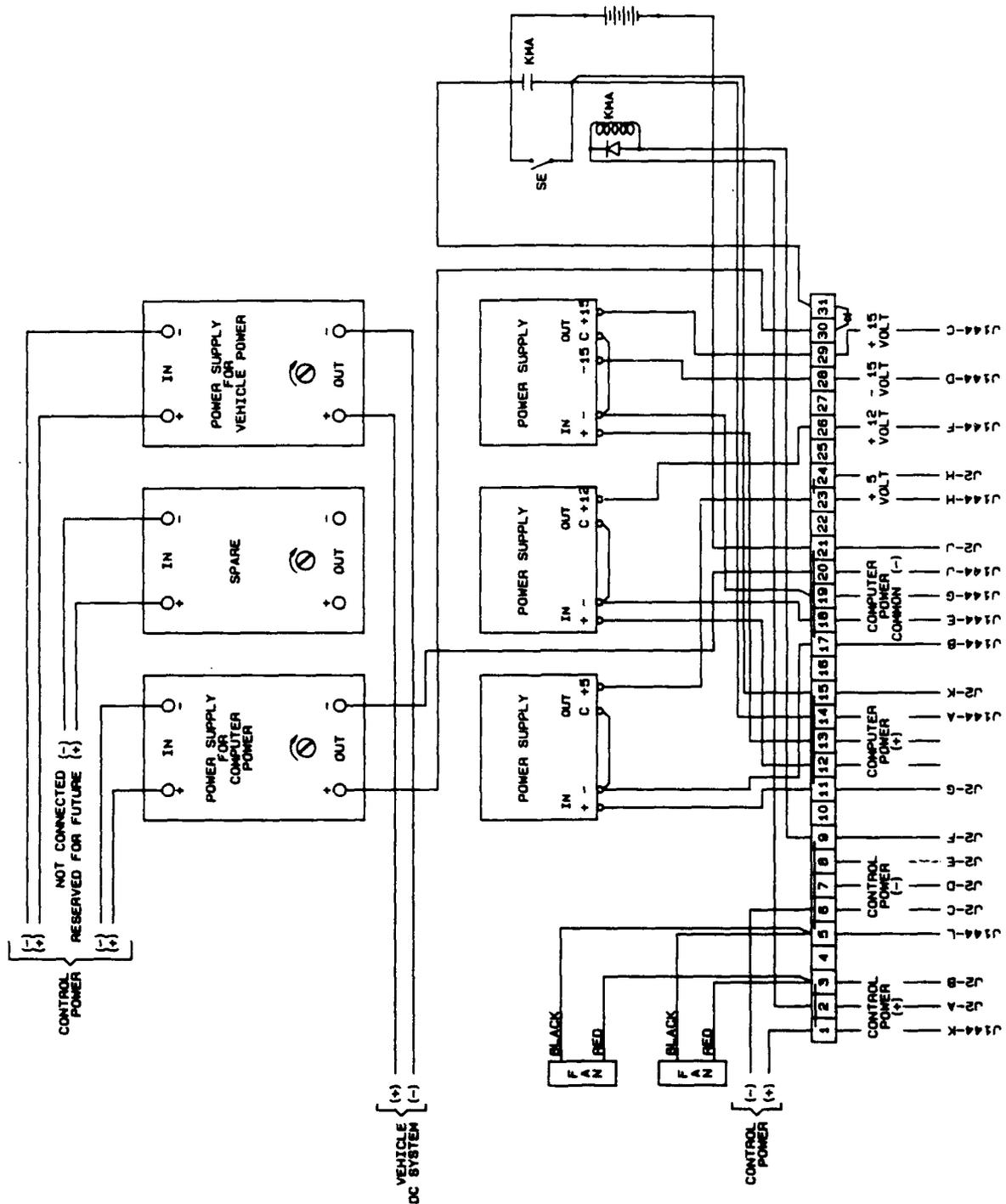
Figure 14. Main Power Supply Box

The BR was designed using a worst case rating of 250 V at 1,600 A for 5 seconds. This corresponds to a complete stop from full speed. An added condition to the worst case scenario is that this stop occurs with no oil flow in the container. Based on the volume and heat capacity of the oil in the container, this stop would cause the oil temperature in the container to go up by 44°C. It is expected that the ambient oil temperature in the BR while the vehicle is operating will be about 82°C. Thus, 82°C ambient + 44°C temperature rise = 126°C. This is well below the flash point of the oil which is 205°C.

INTERCONNECTION SYSTEM AND INTERFERENCE PREVENTION SCHEME

There are 42 input signals to the system computer and 22 output signals, in addition to the power supply inputs and the system status monitors. Interconnection of the various devices which produce and/or use this information involves approximately 75 cables totaling about 1,500 feet.

The main objective of the interconnection system is to transmit the various signals between the components without allowing any detrimental interference, especially to the computer. Probable sources of interference are the drive motor commutators, power relays, control relays, rheostats, power supplies, power rectifiers, generator and motor field controllers, and the radio and intercom system.

The four power systems on the vehicle present a major complication. These systems must be protected from mutual interference and crosstalk.

The basic interference control scheme is to treat the vehicle chassis as a large ground plane that serves as the return conductor for the vehicle chassis systems (lights, horn, etc.) and a sink for the interference signals via the shields from shielded, twisted pair cables. Shielded, twisted pair cables (sometimes called twinax cables) were selected because the twisted pair feature minimizes any magnetically coupled signals, and the enclosing, braided shield provides a path to shunt signals caused by electric fields to ground. Ground loops on the shields are eliminated by assuring that the shield on the cable is only connected to the chassis at one point.

A schematic of the grounding and shielding system is presented in Figure 15.

In addition to the shielded cables, other features were incorporated to minimize interference. A diode is connected across the coil of each relay to eliminate the inductive spikes caused by the switching of the relay. Switches and transducers that do not leave the signal line going to the computer in a floating mode were used; that is, the signal line is always connected to either the signal voltage source or to the power supply return. The power cables to the various devices were routed such that the supply and return are as close together as practical; this helps to minimize the electromagnetic field.

GROUND FAULT DETECTION

The main power bus is capable of operation at 300 V dc and can deliver more than 1,000 A for short periods of time. These voltages and currents can be dangerous; therefore, it is necessary to incorporate some fault detection.

By having the main power bus isolated from all other circuits and the vehicle chassis, a single fault to chassis would not be dangerous to equipment or personnel. Therefore, it was decided to build a detection system to check the insulation integrity of the main power bus each time the MASTER switch is turned on and before the engine is started. By detecting the first fault, personnel and equipment are protected unless there are two separate faults during one operating period.

First fault detection is provided by having the computer perform the following functions:

- Energize the braking grid contactor which connects the positive side of the main power bus to the negative side.

- Energize the ground fault relay which connects the 28 V control power bus (+) to the main power bus, and connect the control power bus (-) to the vehicle chassis through a 600-ohm resistor.

- Monitor the voltage from the VX-1 voltage transducer. If the voltage is less than 0.5 V, then the resistance between the main power bus and the chassis is greater than 50,000 ohms and therefore is acceptable. The transducer voltage will be higher for lower values of insulation resistance, reaching a value of 5 V for zero insulation resistance.

- If the transducer voltage is less than the acceptable value of 0.5 V, the computer will activate the OKAY TO START ENGINE light. If the value is higher than 0.5 V, then an error message will be sent to the operator.
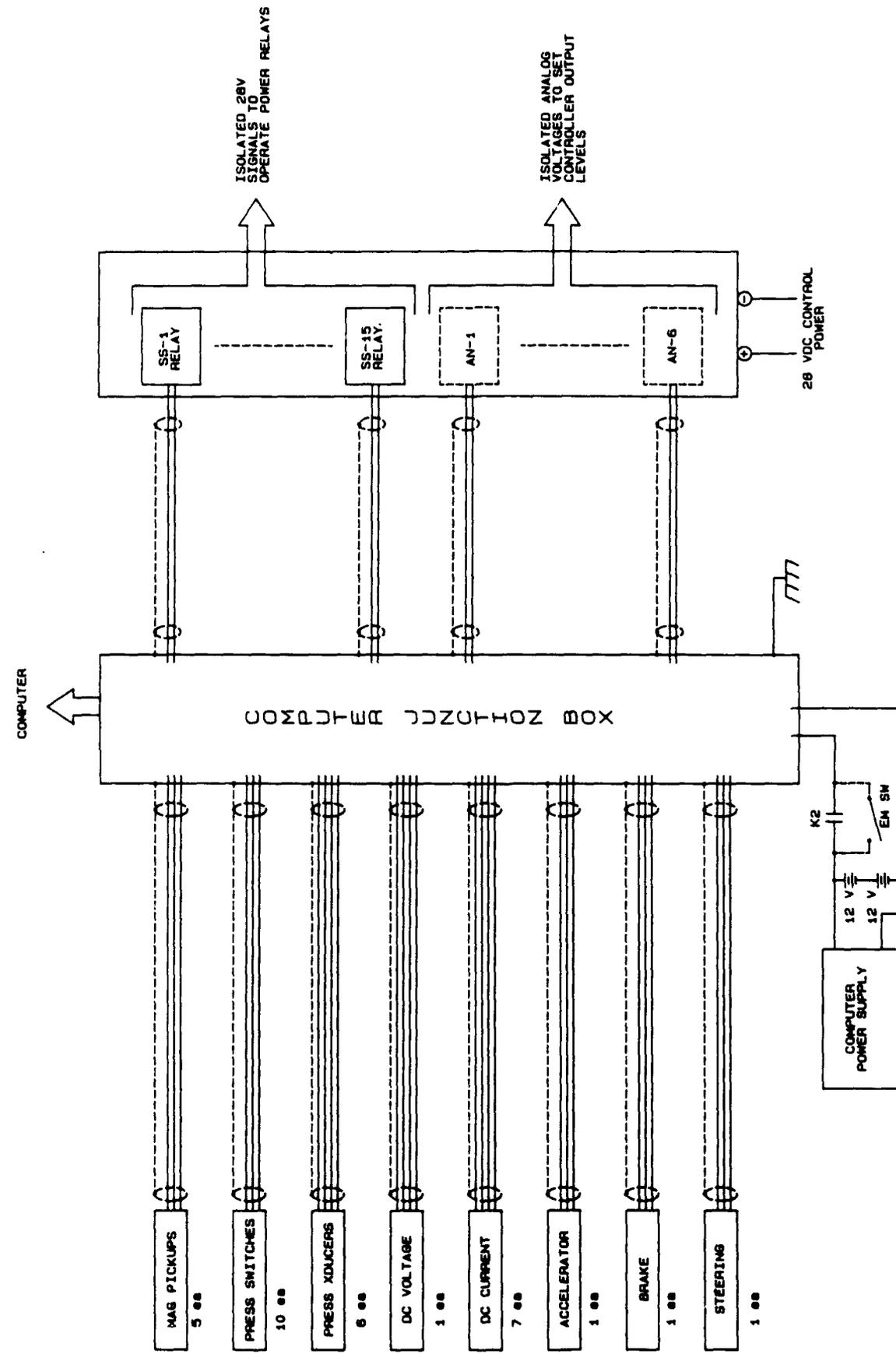
Figure 15. Schematic of Grounding and Shielding System

Section III
Cooling and Lubrication Design

FINAL DRIVE HYDRAULIC SYSTEM (FDHS)

The FDHS provides hydraulic and cooling flow for the FMC final drives and the Mawdsley motor adapter gears. The oil used for this system is MIL-L-2104, which is contained in the 50-gallon sump on the right rear of the vehicle.

A schematic of the FDHS is presented in Figure 16.

The FDHS consists of six dc motors (M1 to M6) which drive 12 pumps (P1A and B to P6A and B), the hydraulic fan pump (P7), which is belt-driven by the diesel engine, various transducers to monitor the status of the FDHS, circuits which control the FDHS based on signals from the main computer or the simulator box, filters, flow dividers, check valves, etc.

Motor M1 powers pumps P1A and P1B. Both pumps draw oil directly from the 2104 sump. P1A supplies 4 gpm through filter F1 to the double brake valve (DBV). The DBV regulates the modulated braking pressure to each final drive brake. The DBV is controlled by the main computer or the simulator box.

In case some system fails and the brakes need to be released, valves V1 and V2 can be manually closed and the brake pressure increased with a hand pump. Increasing pressure releases the brakes.

P1B supplies 5.6 gpm through F2 to the 1:1 ratio flow divider FC-1. The two flows from FC-1 in turn each go to another 1:1 flow divider (FC-2 and FC-3). One output of FC-2 and FC-3 goes to the right and left brake cooling input manifold. The other output of FC-2 and FC-3 goes to cool and lubricate the right and left Mawdsley adapter gears.

Pumps P2A and P3A supply oil through F3 and F4, respectively, to each final drive shifting mechanism. Both of these pumps draw their oil directly from the sump. P2A supplies flow to the right final drive shifting mechanism, and P3A supplies flow to the left final drive shifting mechanism. In neutral, the flow is directed to the HI clutch input port to provide lubrication. Relief valves RV-4 and RV-5 only allow about 1 gpm of lubrication flow in neutral so that the HI clutch is not activated; the excess pressure is bled back to the sump.

Low gear is activated when the computer or simulator box energizes coil B on the right and left final drive shifting mechanisms. This causes flow to be directed to the LO clutch inlet port which engages the low clutch. This flow also provides lubrication for the clutch components.
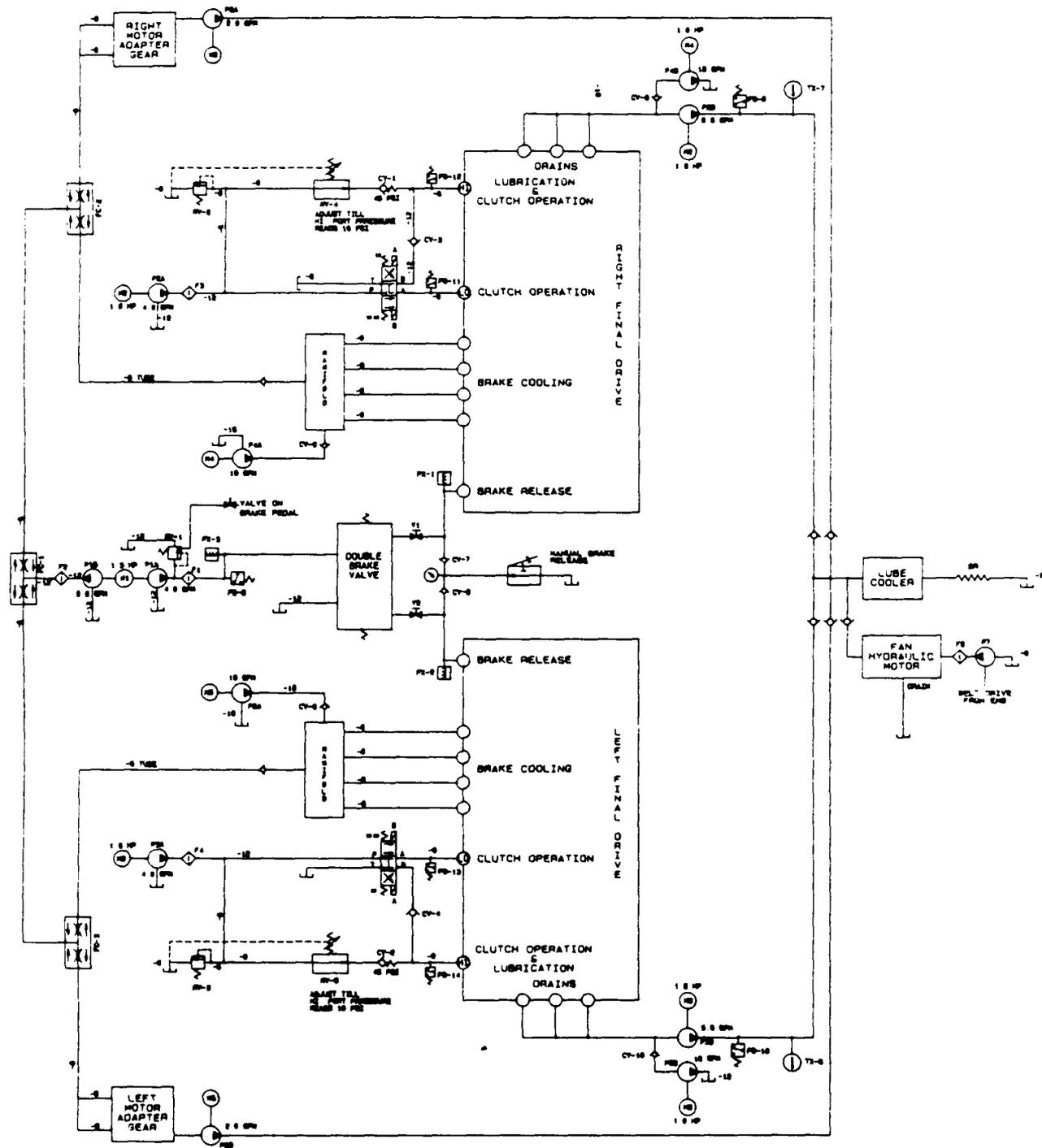
Figure 16. Diagram of Final Drive Hydraulic System

High gear is activated when the computer or simulator box energizes coil A on the right and left final drive shifting mechanisms. This causes flow to be directed to the HI clutch inlet point which engages the high clutch. This flow also provides lubrication for the clutch components.

Pumps P2B and P3B provide scavenge for the right and left final drive, respectively. This oil is directed to the heat exchanger on the diesel engine where it is cooled and sent back to the 2104 oil sump (the BR is located between the heat exchanger and the sump so that the BR always receives cool oil).

Pumps P4A and P5A provide 16 gpm to the right and left brake cooling inlet manifold, respectively. These pumps draw their oil directly from the sump.

Pumps P4B and P5B provide 16 gpm scavenge for the right and left final drive, respectively. This scavenged oil is sent directly back to the sump.

Pumps P6A and P6B provide 2 gpm scavenge for the right and left adapter gears, respectively. This scavenged oil is directed back to the heat exchanger on the diesel engine where it is cooled and directed back to the sump.

ELECTRICAL COOLING SYSTEM

The electrical cooling system provides cooling and lubrication flow for the ac generators, the dc generator, the interphase transformer, the Westech gearbox, and the braking resistor. The cooling oil used for the braking resistor is the 2104 oil; the remaining components use 23699 oil.

Figure 17 shows the electrical cooling system.

Figure 17. Electrical Cooling System
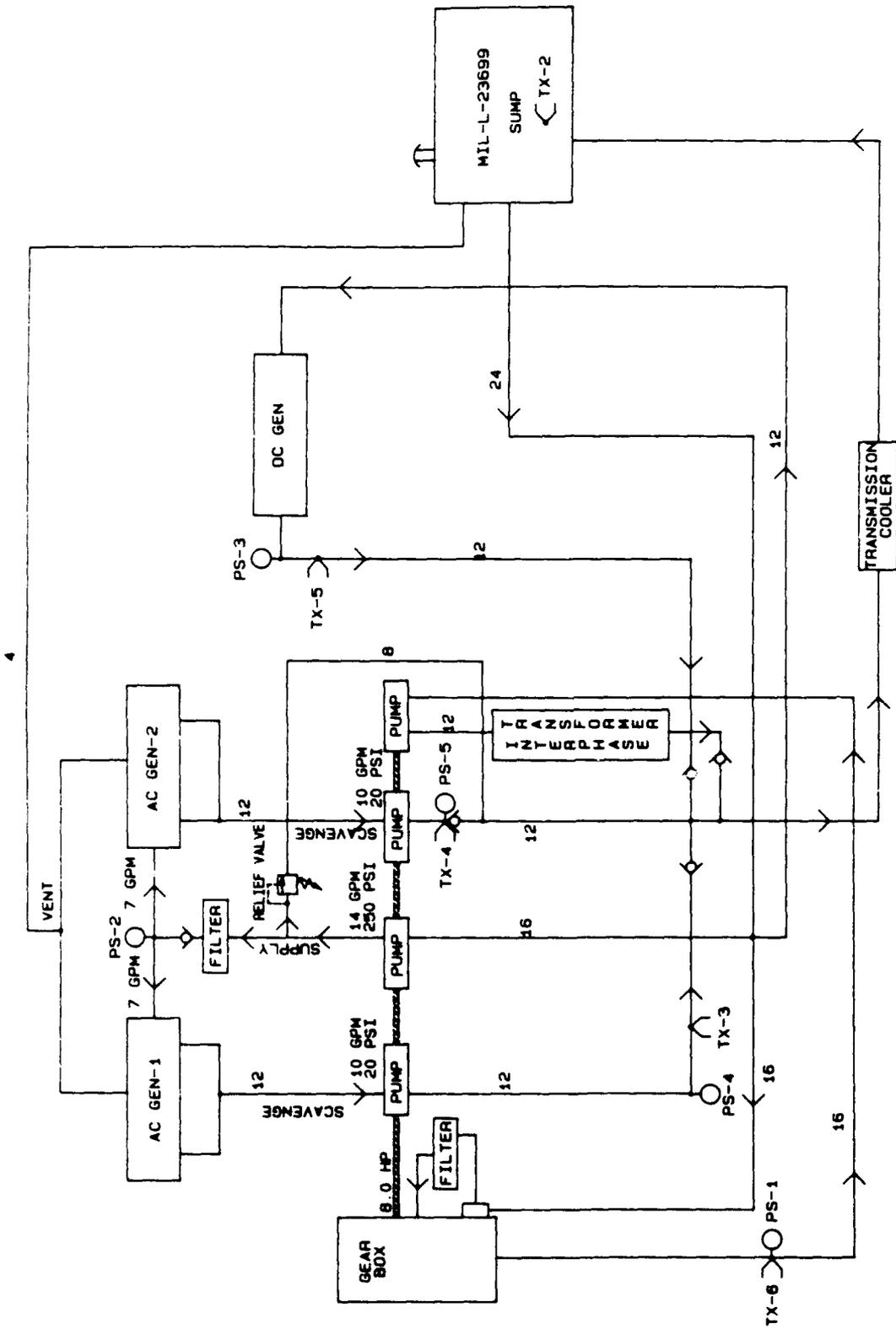
NOTE: Undesignated numbers are SAE hose sizes.

28

Section IV
Control System Design

INTRODUCTION

The control scheme for the electric vehicle speed is based on the dc motor characteristic equations. In this system, the motor field is separately excited by a dc power source. The dc motor circuit model is shown in Figure 18. The characteristic equations governing the motor are:
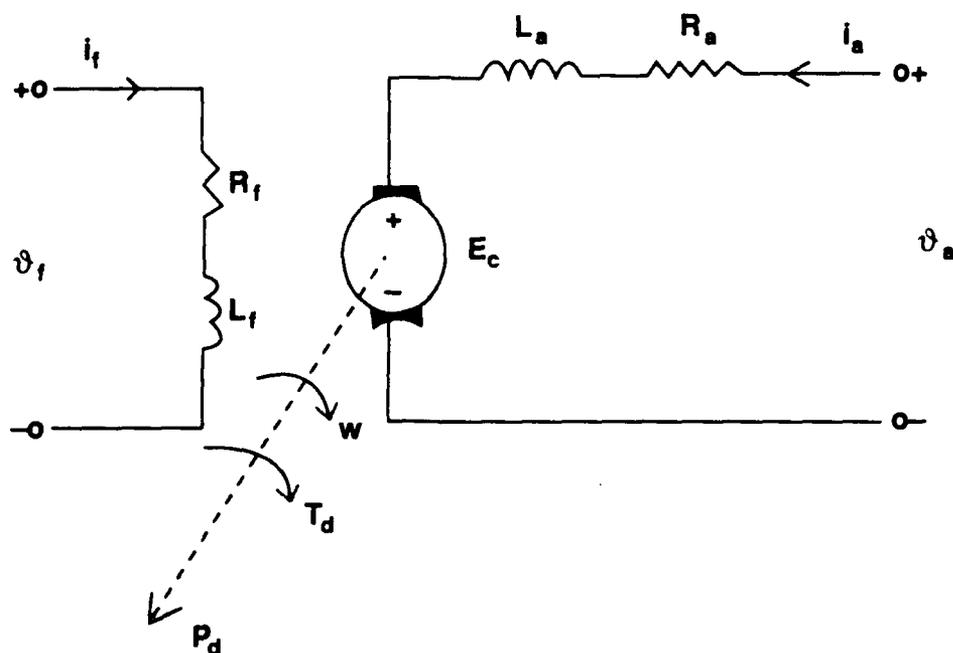
Figure 18. Separately Excited dc Motor Circuit Model

$$V(a) = E(c) + I(a)R(a) + L(a)dI(a)/dt \qquad (1)$$

$$E(c) = K \varnothing w \qquad (2)$$

K = motor constant =Np/a
N = number of turns in armature winding
p = number of poles
a = number of parallel paths
∅ = motor flux
K∅ = non-linear function of I(f)

Under steady state, equation 1 becomes:

$$V(a) = E(c) + I(a)R(a) \tag{3}$$

From equations 2 and 3, the motor speed is:

$$w = (V(a) - I(a)R(a)) / K\emptyset \tag{4}$$

Since $I(a)R(a)$ is very small compared to $V(a)$, equation 4 can be simplified to:

$$w = V(a) / K\emptyset \tag{5}$$

Equation 5 indicates that the motor speed can be controlled by either controlling the armature voltage or the field current. In this vehicle, both the armature voltage and field current are used to control the vehicle speed.

The motor torque is:

$$T(d) = K\emptyset \; I(a) \tag{6}$$

The motor power is:

$$P(d) = T(d) w = K\emptyset \; I(a) \; w \tag{7}$$

From equation 6, $I(a)$ is:

$$I(a) = T(d) / K\emptyset \tag{8}$$

Substitute equations 2 and 8 in equation 1 and solve for $K\emptyset$:

$$K\emptyset = \frac{V(a) + \sqrt{V(a)^2 - 4 \, w \, T(d) \, R(a)}}{2w} \tag{9}$$

The motor dynamic braking power is:

$$
\begin{aligned}
P(\text{braking}) &= V(a)^2 / R(\text{braking resistor}) \\
&= (K\emptyset \, w)^2 / R(\text{braking resistor})
\end{aligned}
\tag{10}
$$

Assuming negligible $I(a)R(a)$ voltage term. Since the braking power is speed dependent, dynamic braking is used to slow down the vehicle, not to bring it to a complete stop.

Equations 2 through 10 constitute the main control equations used in this vehicle.

VEHICLE CALCULATED PERFORMANCE AND CONTROL

Control of vehicle speed is accomplished by control of engine speed, generator field current and motor field current. When starting from a dead stop, three things must happen simultaneously to obtain sufficient motor torque to get the vehicle rolling: increase of motor field current, increase of engine speed, and increase of generator field current to generate enough voltage to produce a motor armature current which, in combination with the motor field, creates the required motor torque. After this initial start up, increase in speed is accomplished by decreasing motor field voltage and increasing generator voltage output; this necessitates an increase of the engine speed.

Vehicle steering is accomplished by control of the motor fields, and steering control is continuously variable with regenerative transfer of energy from one side to the other. When, as an example, a right turn is required, the field on the right motor must be increased, forcing the motor to slow down. At the same time, the field on the left motor is decreased, and the left motor increases in speed. The left motor then tries to drive the right motor with the result that the right motor gets into the generating mode supplying power to the left motor and, in doing so, holding back on the right track while the left motor speeds up the left track and thus forces the vehicle into a right turn.

High speed turns require power delivery to the outer motor greater then the engine can deliver. However, with the regenerative transfer capability, the inner motor operating in the generator mode supplies the difference. This is one of the inherent advantages of the electric drive system. A spin turn is accomplished by reversing the field on one of the motors; a pivot turn is accomplished by disconnecting the inner motor.

The three main goals of the regenerative steering system are: no loss of speed in turns (within power limits), a smooth transition from the straight-ahead condition to the pivot turn condition, and a capability for spin turns when the steering wheel is turned hard left or hard right.

Regenerative steering does not apply in low speed condition. This is because the inner motor becomes a short circuit at low speed ($I(a) = V(a) - E(c) / R(a)$); it does not generate enough electrical power to supply to the outer motor. The inner motor has to be disconnected from the 300 V dc bus in this situation to provide sufficient torque to turn the outer motor.

Reverse operation is accomplished by reversing the direction of field current flow in both motors. This is done by using reverse contactors in the motor field current controllers.

The calculated vehicle performance curves and power audit are shown in Figures 19 and 20, respectively. With 198 hp available from the engine, 160 hp could be delivered to the tracks to operate the vehicle at 40 mph on a straight and level surface assuming 19 hp losses in the final drives.

The control system consists of operator input controls, a digital processor, control software, analog output controllers, and vehicle parameter feedbacks. A block diagram of the basic control function is shown in Figure 21. Figure 22 shows the control interconnection diagram.
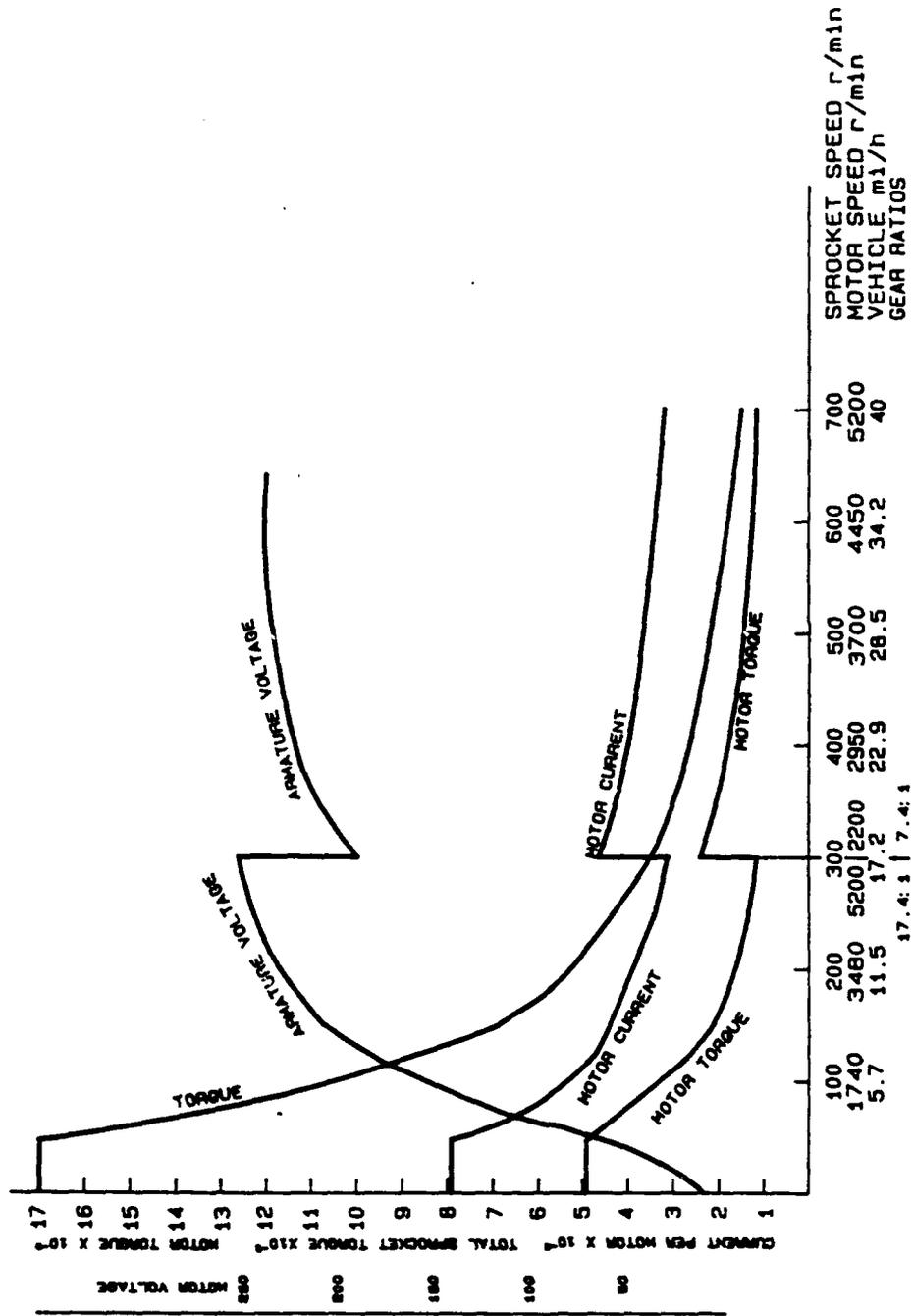
Figure 19. Marine Corps M113—Vehicle Performance Curve
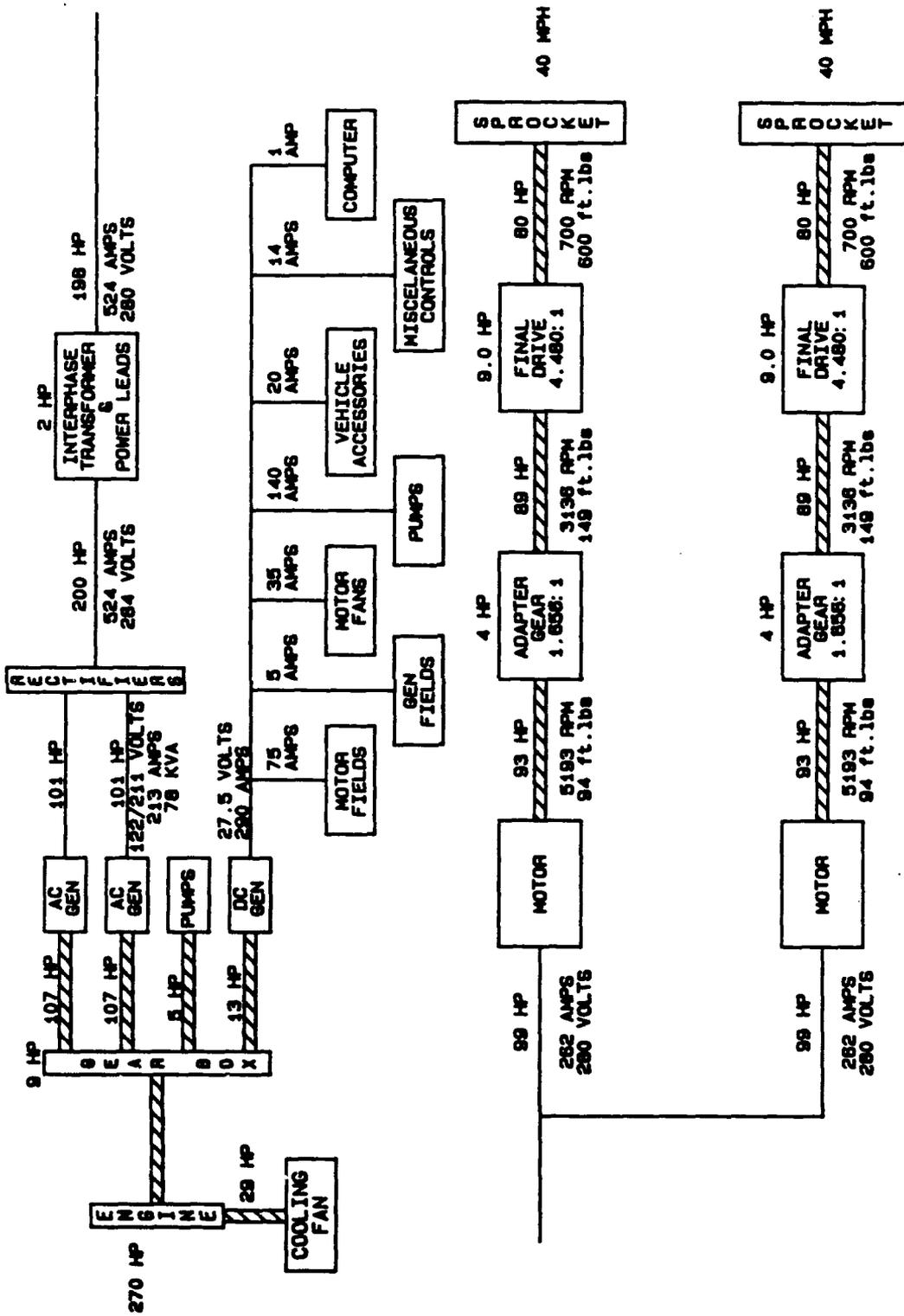
Figure 20. Power Audit—Straight and Level at 40 mph

INPUTS

CONTROL LOGIC

OUTPUTS

OPERATOR INPUTS

GEAR SELECTOR

ACCELERATOR

BRAKE

STEERING

FEEDBACK INPUTS

L&R SPROCKET SPEEDS

L&R MOTOR SPEEDS

ENGINE SPEED

ENGINE TORQUE

P R O C E S S O R

Set speed based on torque, efficiency curve, and anticipated acceleration.

Set field to obtain desired DC bus power flow V x I for desired acceleration rate.

Set magnitude of left and right motor fields based on desired acceleration or deceleration rate. Vary left and right motor fields inversely around the desired rate according to steering position.

Reverse field polarity based on R selector or pivot steering command.

Shift gears based on motor speeds. Hi and Low.

Switch in resistor for dynamic braking.

Engine | Control

Field Controller | Alternator

V x I

Left Field | Reverse Switch

Right Field | Reverse Switch

Left Motor

Right Motor

Right and Left Gear Ratio

Brake Grid

Figure 21. Control Functions for M113 Electric Drive System
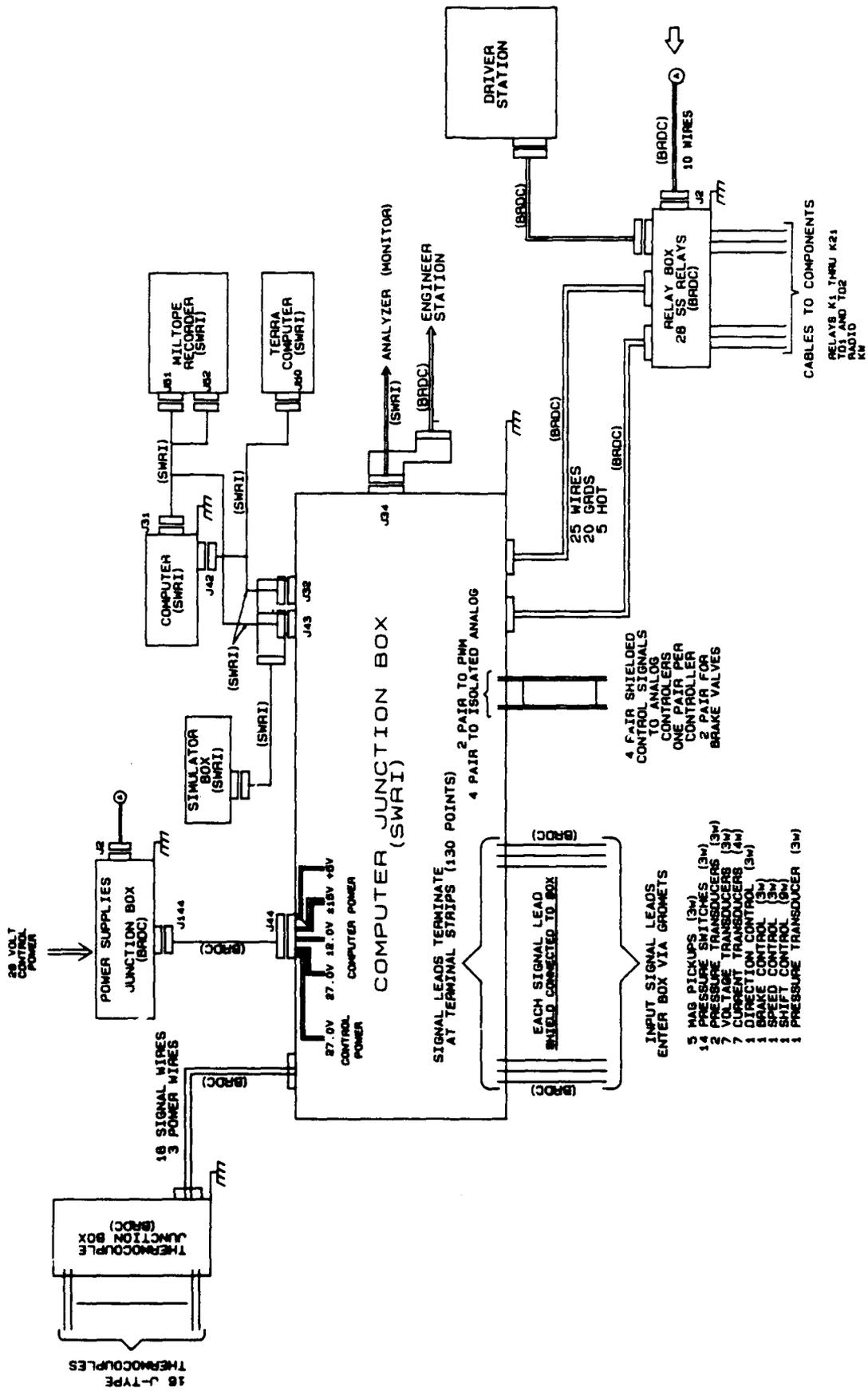
Figure 22. Control Interconnection Diagram

CONTROL SYSTEM THEORY OF OPERATION WITH NARRATIVE EXAMPLES

The control system accepts operator inputs from a steering wheel, an accelerator pedal, a brake pedal, and a gear selector.

The "accelerator" acts as a speed control; that is, its position indicates the desired vehicle speed. The controller senses the difference between actual and desired speed and acts to reduce the difference to zero, either by accelerating or decelerating. The difference between actual and desired speed determines the rate of change that the controller will attempt.

A speed control position of "full on" is interpreted as a signal for maximum acceleration (maximum engine power, if it is possible to use it). A portion of the speed control range is available above maximum speed to indicate maximum acceleration even at high speed.

An indication of desired speed less than actual speed is interpreted as calling for deceleration. The controller responds by slowing the vehicle and applying brakes if needed. This is planned to be at a fixed rate, approximating the vehicle drag that would be encountered on a straight, level, hard surface.

Braking is available in stages:

- Vehicle drag
- Braking grid
- Modulated (gradual) application of the mechanical brakes
- Full mechanical brakes leading to locked tracks

It is planned that maximum use will be made of the "vehicle drag" regime to conserve brakes and reduce cooling requirements.

Braking is initiated in these stages to achieve the desired rate of deceleration. Actuating the operator's brake pedal follows the same schedule with increased pedal pressure or position indicating a desire for greater deceleration. Maximum normal pedal depression causes the controller to proceed rapidly to maximum braking; however, sufficient operator feedback is provided to prevent inadvertent locking of the tracks. Beyond this range of normal operation, the brake control is capable of engaging a mechanical override, requiring high force, which provides a high level of mechanical braking even in the event of control system and electrical failures. This emergency action is done with a mechanical valve which dumps hydraulic pressure and kills the engine through a fuel shut-off mechanism.

The gear selector has six positions:

In **park**, the mechanical brakes are locked; engine speed is controlled by the "accelerator" position. Final drive clutches are released.

In **neutral**, the mechanical brakes are off; engine speed is controlled by the "accelerator" position. Final drive clutches are released.

In **D1**, vehicle starts in low range; shift to high range is controlled by the controller. Vehicle speed is set by the "accelerator" position.

In **D2**, vehicle starts in high range, remains in high range. Vehicle speed is set by the "accelerator" position.

In **reverse**, only low range is available; motor fields are reversed. Vehicle speed is set by "accelerator" position.

In **auto**, the controller switches between low and high range based on desired vehicle speed, fuel efficiency, and safety considerations. Vehicle speed is set by the "accelerator" position.

Moving the range selector to **park** at any time results in maximum application of mechanical brakes through the controller. Moving the range selector to any forward or reverse position with a desired speed indication of zero causes the controller to apply the mechanical brakes. Thus, the controller is programmed to start from a "brake-on" condition and applies the mechanical brakes as a last step in bringing the vehicle to a stop. As stated above, moving the selector to neutral releases the brakes.

The controller sets engine speed through a governor. The controller outputs a desired engine speed signal to the governor which acts to maintain that speed within the capability of the engine. The controller selects engine speed based on required power and fuel consumption data. The rule of thumb is that the controller aims for the condition of lowest fuel consumption. Some "headroom" is provided, however, to preclude bogging down on hills. Instantaneous power (dc bus current and voltage) is monitored and compared to available power; engine speed is adjusted accordingly.

The controller sets alternator field current and right and left motor field currents through pulse width modulation (pwm) type field controllers. Except during starts from zero speed, maximum alternator field current is set as a function of alternator speed. When starting from zero speed, dc bus voltage is limited through alternator field current in order to limit in-rush current to the motor armatures. Motor field currents are set to give the torque required to maintain speed or accelerate. This method requires some implementation of the late Carl Heise's motor torque curves. Steering is accomplished by setting left and right motor field currents to obtain the desired left and right track speeds. It is assumed that turning requires more power than going straight; therefore, engine speed is adjusted to maintain vehicle speed in a turn.

Steering input is provided by a potentiometer type device operated by a steering wheel. This input is used to develop a desired left and right track speed based on desired vehicle speed. These are used to set the motor field currents. Average desired vehicle speed will be maintained in a turn. It is planned that steering will proceed smoothly from large to small radius turns into a pivot turn, and finally into a spin turn. As the turn becomes a pivot or spin turn, desired vehicle speed ("accelerator" position) is interpreted as desired rate of turn through the sprocket speed.

For a given radius turn, the same ratio of motor field currents is used for steering while braking, while accelerating, or at constant speed. The magnitude of the currents is adjusted based on speed and torque.

The controller manages the final drive range through control of the final drive clutches and, if necessary, synchronizes shifting through control of the motor speeds. Shifting time delay can probably be reduced if some form of "bang-shifting" is implemented. This depends on the amount of energy which must be dissipated by the clutches during a shift. During a shift

sequence, the controller calculates the new motor speeds and torques, corresponding engine speed, and motor and alternator fields required. The controller then disengages the first clutch and begins moving engine and field controls to the new operating point. The controller then engages the second clutch without attempting to synchronize speeds. The exact sequence and time delays depend on clutch, hydraulic, and machine time constants. The controller shifts both final drives at the same time.

The controller provides both up- and down-shifts automatically in D1. Some hysteresis is included in the shift algorithms. Shift points are variable in response to torque requirements. The controller makes the required calculations and comparisons to maintain the allowable envelope of operating areas for critical components.

Example 1

The vehicle is stopped with the engine running in park on level ground. The operator selects neutral; the controller releases the brakes (assuming the operator has not otherwise applied brakes). The operator selects D2; the controller sets the brakes and engages the high range clutches. The operator depresses the accelerator pedal, signalling for moderate speed. The controller releases the brakes, sets the motor field currents to max, ramps the engine speed to a predetermined value, and sets alternator field current to the appropriate level to limit the inrush current to the armature to 800 A. As the vehicle accelerates, the controller monitors v and dv/dt and adjusts motor field and engine speed to provide the torque and power required with adequate "headroom" to preclude bogging down. Once desired speed is reached, the engine speed is set for fuel efficiency, and the motor field is set to maintain speed. Small inclines can probably be overcome by automatic adjustment of the governor within the excess power capability of the engine. The controller monitors v and dv/dt and instantaneous power; the engine speed is adjusted to maintain a small excess power capability. A steering input causes the motor fields to be adjusted to the desired turn radius, keeping the average vehicle speed equal to desired vehicle speed. Turn radius is limited as a function of speed so as not to exceed acceptable values of mv^2/r.

If the operator starts in D1, the controller manages the automatic shift at the appropriate point by disengaging the low clutch, adjusting motor and alternator parameters to desired values, and engaging the high clutch. The shift point is variable based on torque requirements above some fixed minimum speed.

Example 2

The vehicle is moving straight ahead at a moderate speed (roughly, 30 mph) on a hard, level surface. The operator moves the "accelerator" pedal to indicate a lower, non-zero speed. On a continuous basis, the controller monitors a quantity which characterizes "vehicle drag"; at a constant speed, it is the average power to maintain speed; under acceleration, it is the average power less $m*v*(dv/dt)$. The controller is programmed to decelerate in proportion to delta v. The controller compares the requested deceleration rate with that available from each braking regime and selects the appropriate action. (Moving the "accelerator" pedal to zero under the stated conditions would cause the controller to bring the vehicle to a stop using vehicle "drag.") The controller reduces the alternator field current and adjusts motor field current to maintain torque at the new speed. If the power required at the new speed would allow more efficient engine operation at a different engine speed, the engine speed will be adjusted based on fuel efficiency data.

Example 3

The vehicle is moving straight ahead at moderate speed uphill. The operator moves the accelerator to indicate zero speed. The controller compares apparent "vehicle drag" (i.e., the effect of all forms of resistance, including the hill) with the programmed rate and determines that "vehicle drag" under the circumstances will result in more rapid deceleration than the programmed rate. Therefore, the controller applies positive power at a reduced rate to allow the vehicle to slow at the standard programmed rate. This is accomplished by reducing the alternator field current gradually. The engine speed is also decreased as the power required decreases.

Example 4

The vehicle has been traveling at constant speed uphill; it crests the rise and starts down a steep incline. The operator decides that a lower speed would be prudent and moves the "accelerator" to a significantly lower speed indication. The controller compares desired rate of deceleration with the available braking regimes and recognizes that effective "vehicle drag" would allow the vehicle to speed up but that the braking grid is capable of providing the desired deceleration. The controller reduces dc bus current to zero (through control of the alternator field current), and closes the braking grid contactor. The motor field current is ramped up to achieve desired deceleration. These actions may take sufficient time and some immediate application of mechanical brakes may be required to prevent speeding up while the braking grid is being energized.

If the effect of the grade is such that the braking grid is insufficient, the controller, in addition, applies the mechanical brakes in a controlled, gradual manner. The controller provides a signal to control the position of a valve which allows the spring-applied brakes to act. This signal allows the mechanical brakes to be controlled bidirectionally over the range from full-off to full-on. Because the existing brakes were not designed for this service, use of the mechanical brakes may have to be minimized. However, at low speed where dynamic braking is negligible, mechanical braking is expected to be essential. Full-on clamping of the mechanical brakes at that point seems undesirable.

The operator can demand a greater rate of deceleration (than the preprogrammed rate) by use of the brake pedal. The controller will respond to increased pedal depression or pressure with increased deceleration up to the limit of the system. It will respond in a manner similar to that described above using the appropriate regime(s) ranked in the same order.

Example 5

The vehicle is on a level surface moving forward and decelerating under the vehicle drag regime. The operator turns the steering wheel clockwise for a moderate right turn. The controller sets the ratio of motor field currents to obtain the desired left and right track speeds for the desired turn radius. The magnitude of the currents is set by the desired rate of deceleration. One motor (the right) now acts as a generator feeding power to the other motor (the left) and allowing steering control through the motor field currents as in the powered case. In order to maintain the same deceleration rate, it may be necessary to supply some positive power from the bus.

If the vehicle is decelerating in the braking grid regime, the same ratio of currents is used to obtain the desired turn radius. The magnitude of the currents is set to obtain the desired rate of deceleration.

DC MOTOR FIELD CURRENT CONTROLLERS

The motor field current controller is a 500 Hz, pwm-controlled transistor chopper type. A 300 A/ 450 V single Darlington transistor is used as the main power switch.

The transistor base drive circuit consists of a MOSFET that is controlled by pwm integrated circuits. Figure 23 shows the transistor base drive control circuit.

The action of the Darlington transistor chopper is to apply a train of unidirectional voltage pulses to the motor field winding. The pwm control circuit keeps the overall period $T(on) + T(off)$ constant but varies $T(on)$, hence varies the average motor field voltage or current. The ratio of $T(on)$ over $T((on) +T(off))$ is the duty cycle of the voltage pulses which is varied from 0 to 96%. Figure 24 shows the transistor chopper circuit.

The input to the field current controller is a 0 to 5 V control signal from the computer; the controller provides a proportional output of 0 to 165 A to the field winding of the dc motor. There are two motor field current controllers in this vehicle: one for the right motor and one for the left motor. The controller is a closed loop system using current feedback. The controller closed loop control block diagram is shown in Figure 25.
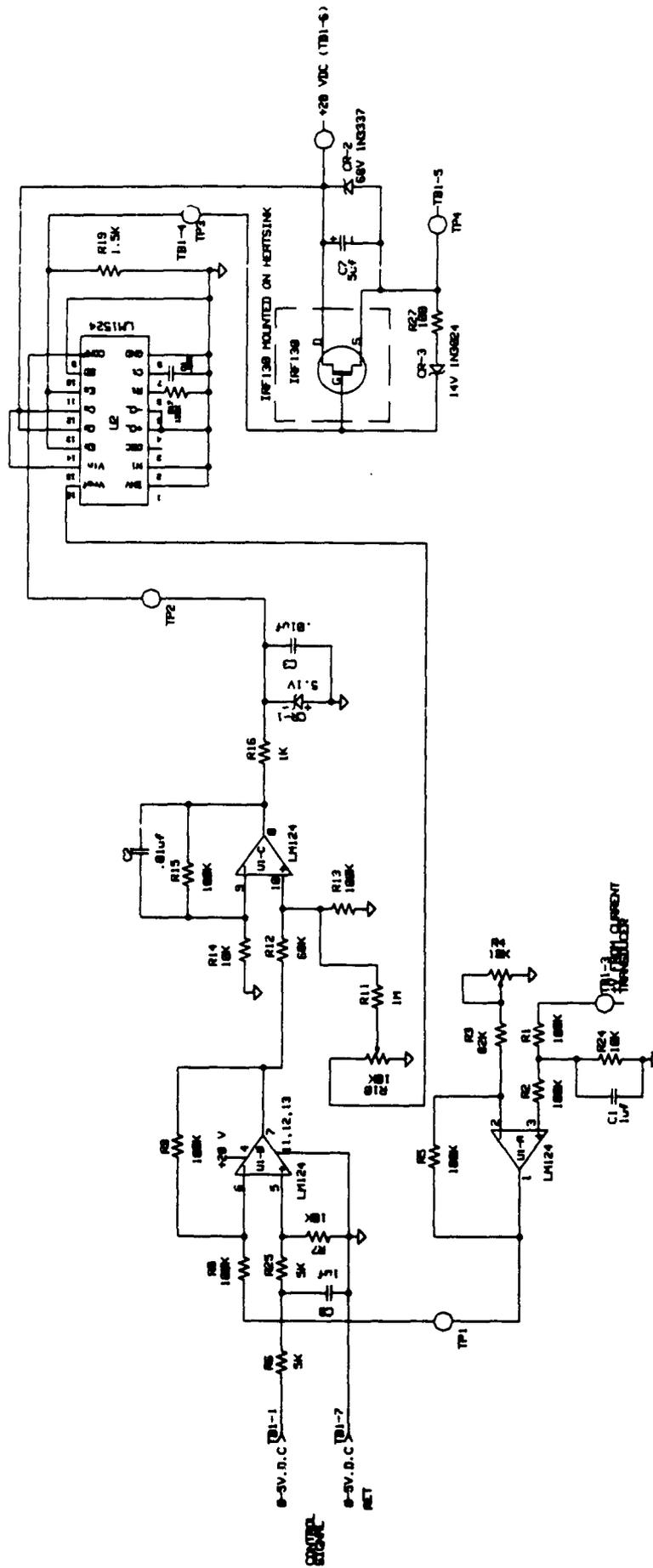
Figure 23. Motor Board

41

NOTES: UNLESS OTHERWISE SPECIFIED.
1. ALL RESISTANCE VALUES ARE IN OHMS.

2. ALL CAPACITANCE VALUES ARE IN MICROFARAD.
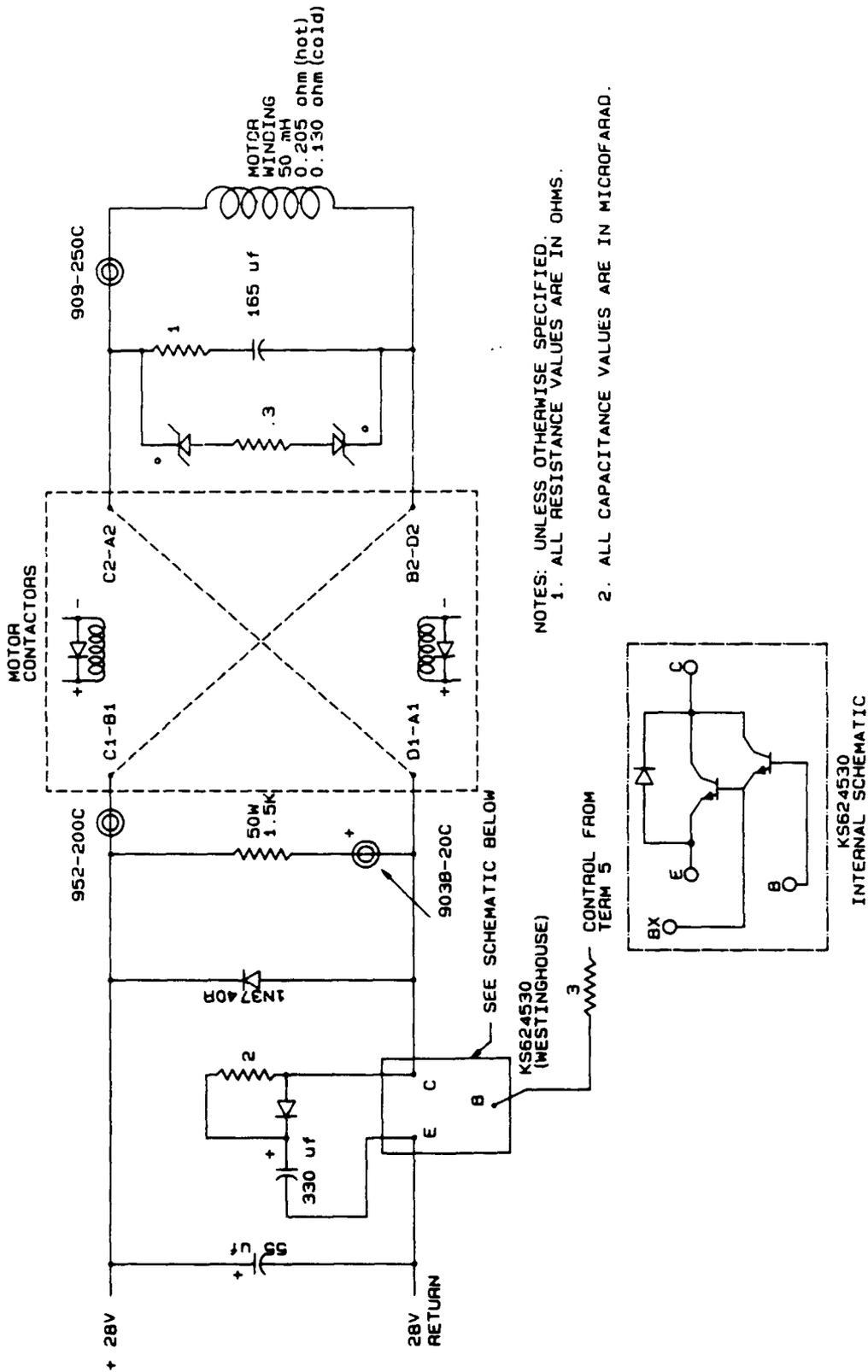
Figure 24. Controllers for Electric Drive Motors

Figure 25. Motor Field Current Controller—Closed Loop Control Circuit
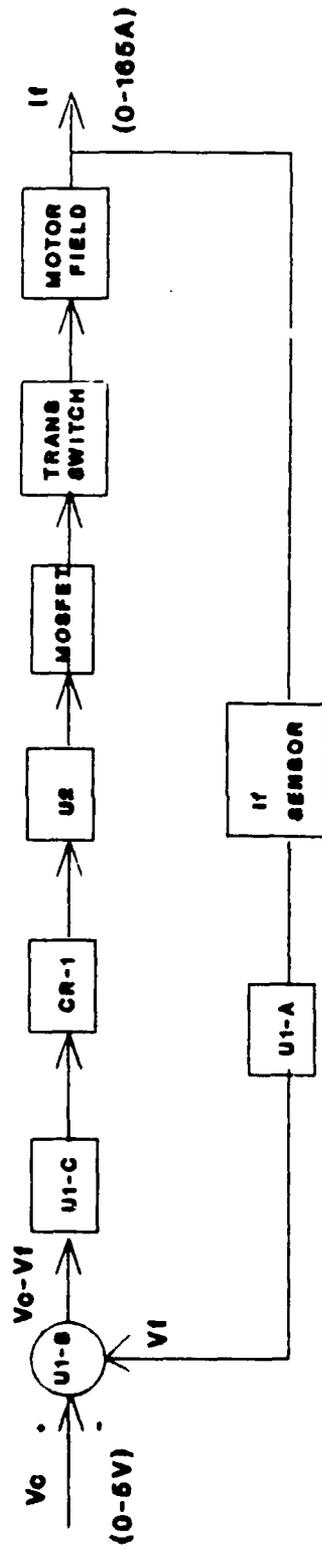
U1-A - FEEDBACK AMPLIFIER

U1-B - DIFFERENTIAL AMPLIFIER

U1-C - VOLTAGE AMPLIFICATION & FILTERING

U2 - LM1624 PWM

CR-1 - ZENER DIODE

AC GENERATOR FIELD CURRENT CONTROLLER

The generator field circuit is also a pwm type controller which operates at 1,000 Hz. The main power switch for this controller is a MOSFET; the pwm control circuit for the MOSFET is similar to the one in the motor field current controller.

A block diagram of the ac generator field controller circuit is presented in Figure 26. A schematic diagram of the circuit is presented in Figure 27.

The field controller receives a 0 to 5 V analog signal from the computer and outputs to each generator field a current of 0 to 4.0 A. There is a rheostat in the controller that permits the outputs of the two generators to be balanced at a specific operating point. This adjustment is necessary because without it the controller will provide each generator with exactly the same field current. The two generators are not identical; therefore, being driven at the same speed and receiving the same field current will produce different output currents. The load point at which the rheostat is used to balance the load is approximately 1,000 A, which is the combined continuous current rating of the two generators. Unbalance becomes greater at lesser currents, but this is no problem since neither generator's current is greater than 500 A. The generator field controller is located in the front right corner of the passenger compartment.

ENGINE SPEED CONTROLLER

The engine speed is controlled by an electric governor, which is controlled by the SwRI digital computer. The electric governor consists of a United Technologies electric governor control unit (CU 671C-7), an AGB 200 actuator, and an AMBAK RSC 671 ramp generator. The governor controls the engine speed from 700 to 2,800 r/min proportionally to the 0 to 5 V computer control signal. At a given input voltage, the governor will control the engine speed to within roughly ±2%.

The governor is a closed loop system, which keeps the engine speed at the level set by the computer independent of the load on the engine. This means that sudden transient loads on the vehicle, such as going up a slight grade, can be handled by the governor until the computer recalculates the desired speed.

A schematic diagram of the engine governor circuit is presented in Figure 28.
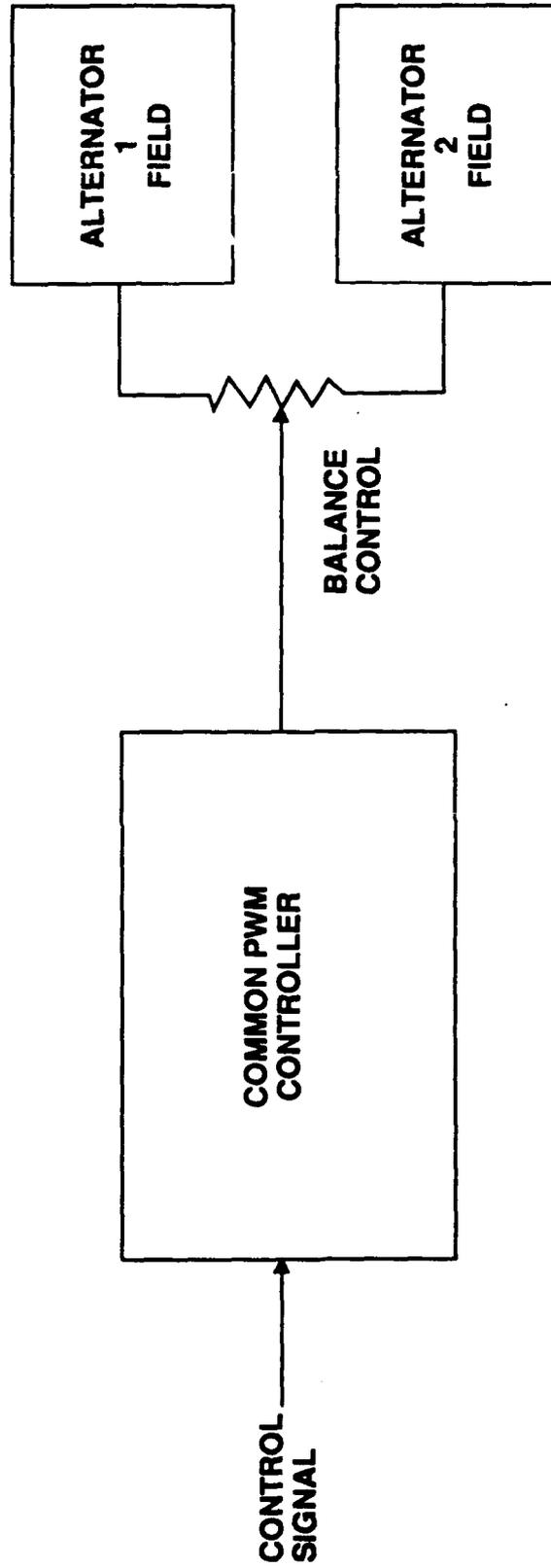
Figure 26. Dual Alternator Field Controller
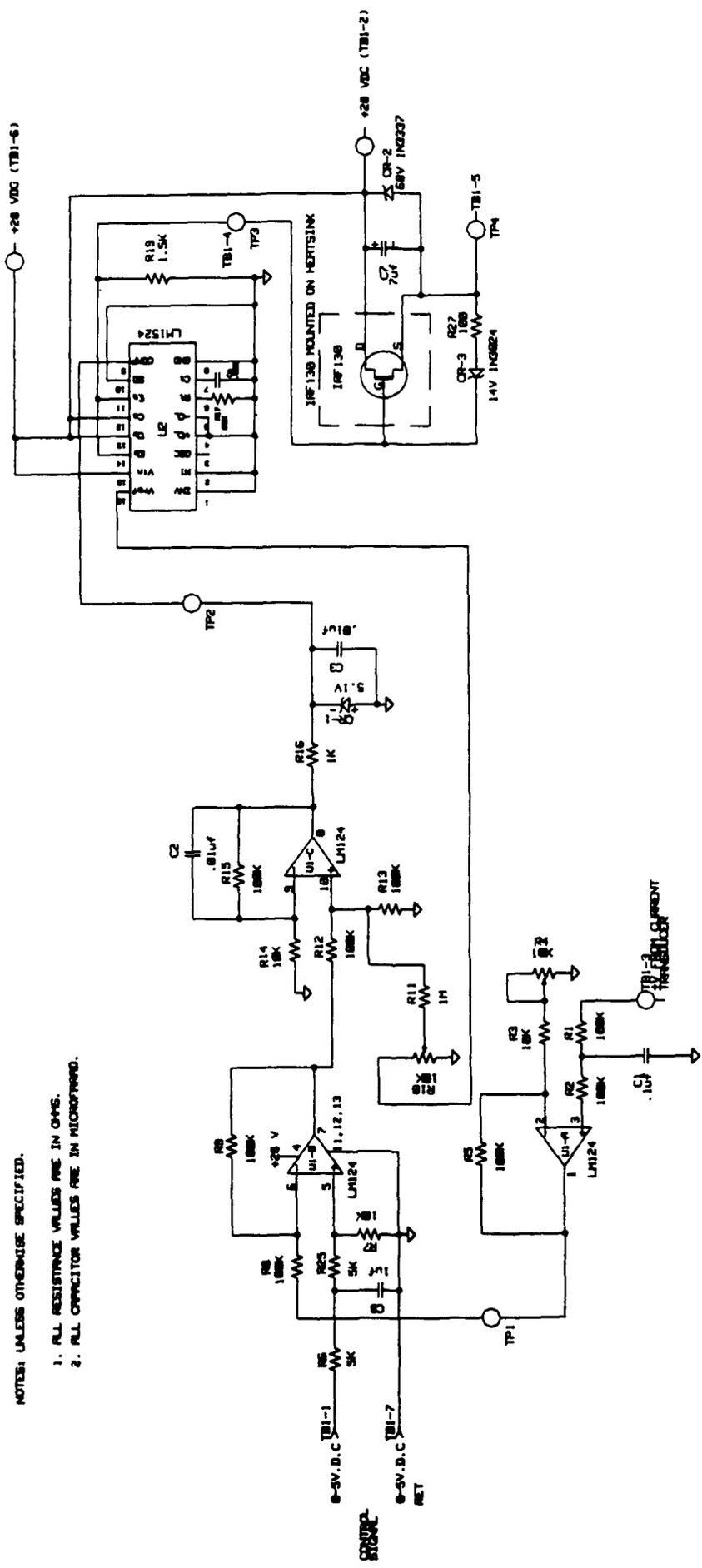
Figure 27. Schematic of ac Generator Field Controller
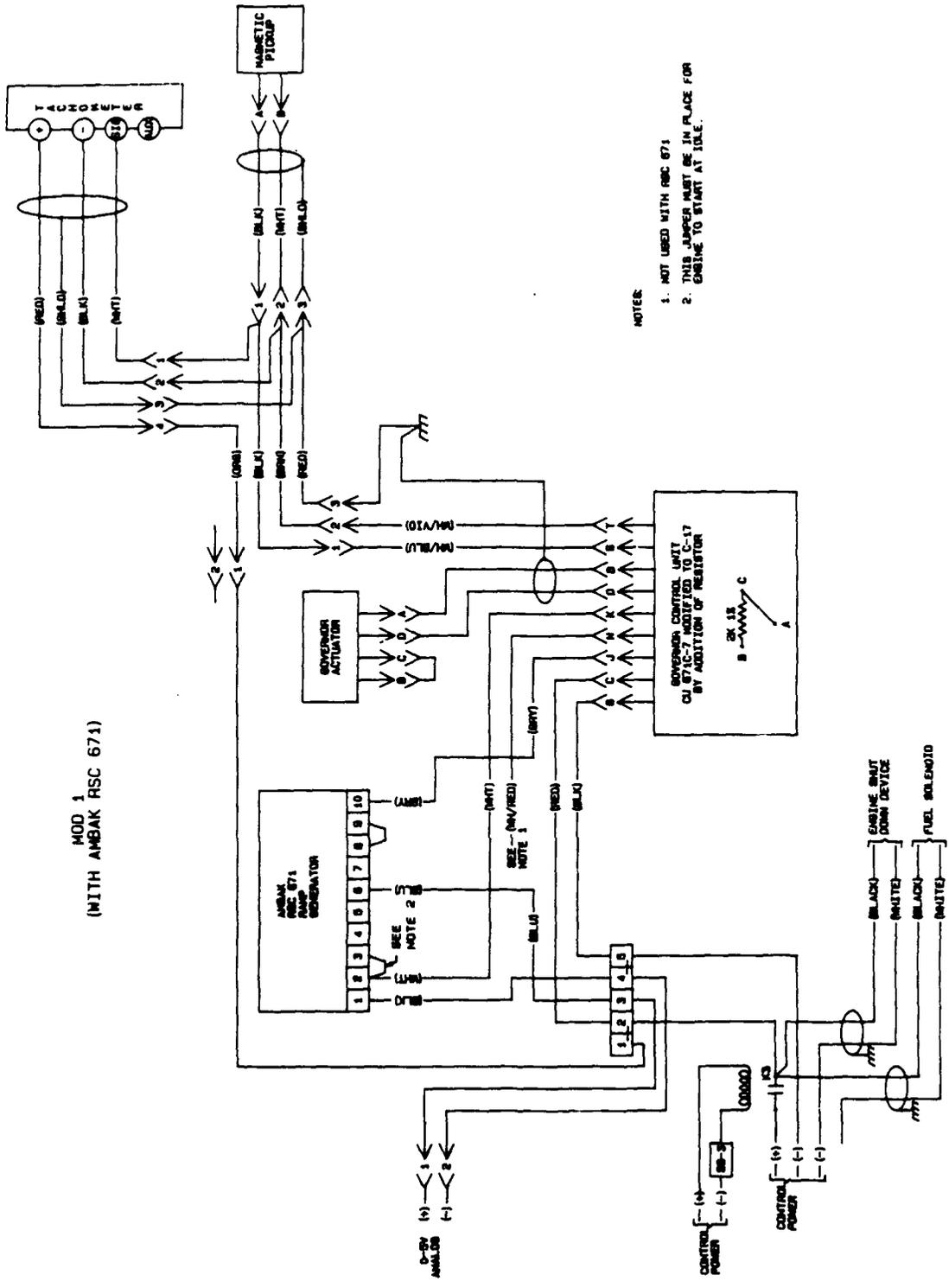
Figure 28. Schematic of the Engine Governor Circuit

SwRI CONTROL SYSTEM HARDWARE

This section briefly describes the various components which comprise the computer control system developed for the vehicle. Volume 4 provides a complete description of the SwRI control system hardware.

Control System Microcomputer. The SwRI computer control system hardware consists of the 5 MHz Intel 8086 central processing unit, 8087 math processor, 8089 input/output processor, and associated A/D, D/A, and F/D converters.

Junction Box. The junction box (JB) is the primary relay and transfer point for all of the control system wiring in the vehicle. It is through the JB that the control computer receives data and status signals from the vehicle systems and power from the 28 V dc supply. The outputs from the main computer are sent through the JB to the circuits which control the vehicle drive system.

Monitor Box. The monitor box, supplied to BRDEC by SwRI, can be used instead of the engineer's station to view the value of various voltages and frequencies occurring within the electric drive and computer control systems. To use the monitor box, disconnect the cable which goes into the engineer's station and connect it to the monitor box connector jack.

Simulator Box. The simulator box is an analog control circuit designed to emulate the control functions of the main computer. The simulator box is to be used whenever the main computer is not connected or not functioning properly. The simulator box uses the same input cable which goes into the main computer. The simulator box does not have the ability to send data to the MILTOPE recorder.

Terra Computer. The Terra computer has a keyboard which allows test engineers to modify the software routines in the main control computer should this become necessary. The Terra also has a single line display which allows the test engineer to see error messages should an error occur within one of the vehicle systems.

MILTOPE Recorder. The MILTOPE data tape recorder logs information from the various vehicle systems for later analysis and documentation.

COMPUTER INPUTS

The computer input signals come from the magnetic pickups, pressure switches, pressure transducers, current transducers, thermocouples, and operator controls. A listing of the computer inputs is presented in Appendix A. The operator control inputs consist of a steering wheel, accelerator pedal, brake pedal, and gear selector.

Steering Wheel. The steering wheel is connected to a self-return spring so that it will remain at center when the driver is not applying force to the wheel. Also connected to the steering wheel is a potentiometer which outputs a proportional 0 to 5 V depending on the angle of the steering wheel with 2.5 V indicating that the steering wheel is in the center position. A left turn is indicated by 2.28 to 0.345 V with 0.345 V being hard left. This corresponds to a steering wheel angle of -15 to -145 degrees. A right turn is indicated by 2.72 to 4.56 V, with 4.56 V being hard right. This corresponds to a steering wheel position of 15 to 145 degrees. The steering wheel potentiometer voltage is sent to the computer along input line DC-1.

Accelerator Pedal. The accelerator pedal is connected to a potentiometer; the desired vehicle speed is a function of this signal and the brake pedal signal. The potentiometer outputs a proportional 0 to 5 V signal, depending on the accelerator pedal's displacement angle with 5 V indicating maximum acceleration.

Brake Pedal. The brake pedal is connected to a potentiometer which outputs a proportional 0 to 5 V signal depending on the brake pedal's angular displacement, with 5 V indicating no brake and 0 V indicating full brake.

Gear Selector. The shifter is installed on the engine bulkhead wall on the driver's right side, and is situated to be operated by the driver's right hand.

The different positions of the shifter are generated into an 8-bit Gray code by an absolute position shaft encoder. The Gray code is used because it is easy to verify its accuracy. When the shifter is moved, the control system will not switch into a new gear until it recognizes a new, valid 8-bit code. There are six possible shifter positions and 256 possible codes, thus there are numerous codes which indicate any one position of the shifter. The codes which do not indicate a valid position are ignored by the computer. The shifter has the following possible positions: **park, neutral, D1** (low gear), **D2** (hi gear), **reverse** and **automatic**. In the **automatic** position, the control system will control the shifts between **D1** and **D2**. The signal from the gearshift is sent to the computer along line GS-1.

The **park** position of the shifter causes the following actions:

- The computer completely activates the modulated brakes on the final drives.

- A mechanical switch opens, which causes a circuit to completely activate the modulated brakes. This is a fail safe measure in case the computer should fail and turn off the modulated brakes.

Figure 29 shows the operator interface controls circuit.

COMPUTER OUTPUTS

The output signals from the computer are digital, analog, and pulse width modulated (pwm) signals. The digital signals control the solid state (SS) switches which are used to energize the vehicle's various power relays and contactors.

The analog signal outputs control the dc motor field current controller, the ac generator field current controller, and the engine speed controller. The pwm signal outputs control the final drive hydraulic braking system.

A description and listing of the digital and analog output control signals are presented in Appendix B.
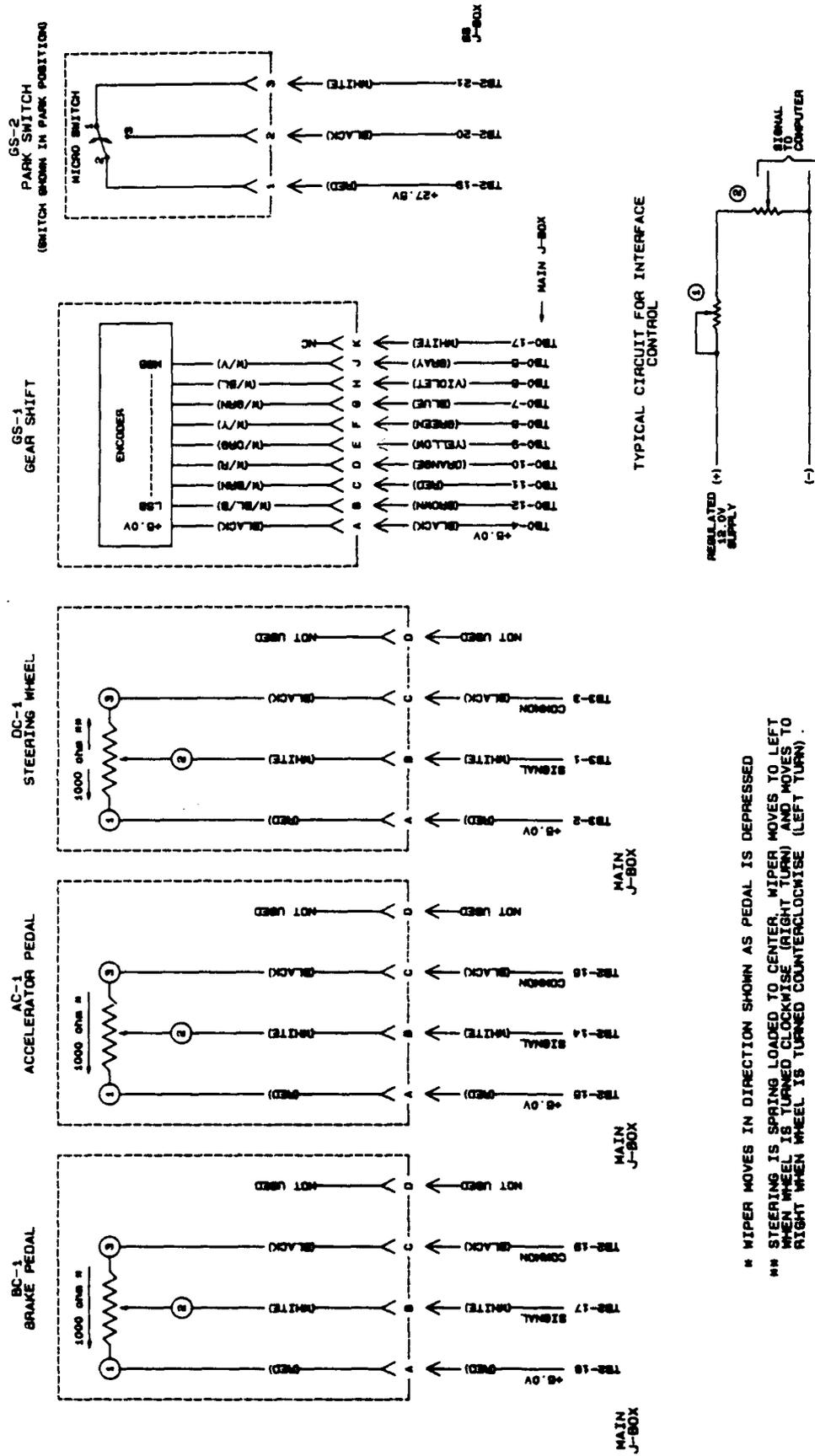
Figure 29. Operator Interface Controls

ENGINEER'S STATI N

The engineer's station includes a meter panel and indicator lights which monitor various vehicle parameters. Following is a list of the indicator lights and meters on this station and their functions:

The **lube press** light refers to the engine lubrication system pressure and turns off when this pressure goes below 5 psi.

The **cooling press** light refers to the hydraulic pressure to the engine cooling fan and turns off when this pressure goes below 500 psi.

The **gearbox press** light refers to the lubrication pressure in the Westech gearbox and turns off when this pressure goes below 50 psi.

The **ac lube press** light refers to the lubrication pressure for the Bendix ac generator and turns off when this pressure goes below 50 psi.

The **dc lube press** light refers to the lubrication pressure in the Bendix dc generator and turns off when this pressure goes below 50 psi.

The **#1 and #2 SCAV** lights refer to the lubrication scavenge pressure for the #1 and #2 Bendix ac generators. These lights turn off when the scavenge pressure goes below 5 psi.

The right and left **LO clutch** lights will stay on while the low clutch is activated.

The right and left **HI clutch** lights will stay on while the high clutch is activated.

The right and left final drive **SCAV OK** light will stay on while the scavenge pressure is above 3 psi.

The **test** button allows testing of all the lights on the panel.

The **control power** meter measures the dc control system power bus voltage. This voltage should be around 28 V when the **master control switch** is on.

The **dc bus volts** and **amps** meters measure the vehicle main dc electrical power that supplies the two dc motors to drive the tracks. During vehicle operation, the maximum main dc bus voltage is about 300 V; the maximum bus current is about 1,600 A. The bus current will go in the negative direction under an electrical braking condition.

The **computer power** meter measures the computer system power bus voltage. This voltage should be around 28 V dc when the **master control switch** is on.

The **left drive motor field amps** and **armature amps** meters measure the field and armature currents in the left motor. During vehicle operation, the maximum field current is about 165 A; the maximum armature current is about 800 A. The field current goes in the negative direction when the vehicle goes in the reverse direction. The armature current goes in the negative direction during a regenerative steering or electrical braking condition.

The **right drive motor field amps** and **armature amps** meters measure the field and armature currents in the right motor.

The **final drives press** meter measures the final drive input brake pressure.

The **left brake press** meter measures the left final drive brake pressure.

The **right brake press** meter measures the right final drive brake pressure. A drawing of the engineer's station panel is presented in Figure 30.
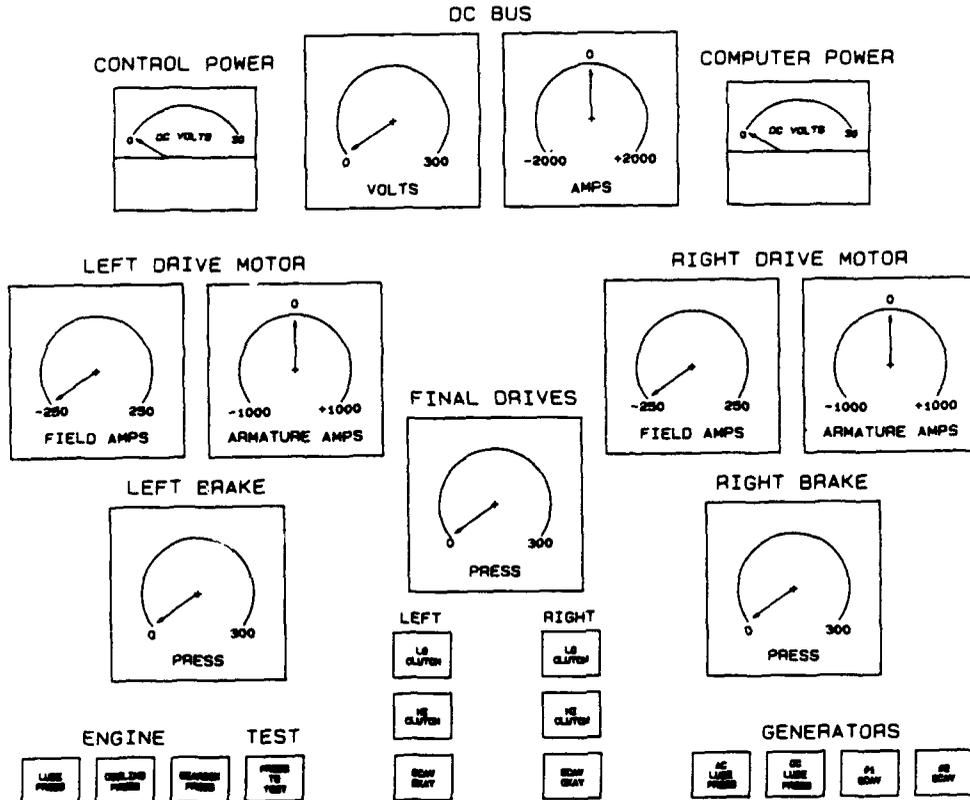
Figure 30. Engineer's Station Panel

DRIVER'S STATION

This station includes various indicator lights and switches to control the vehicle and to keep the driver informed of the vehicle status. The station includes the following:

The **engine control** switch allows the driver to start and shut off the engine.

The **computer resume** switch is used to resume the computer operation after an interrupt. The software continues from the point of interruption.

The **event marker** switch places a marker signal onto the data recording tape. This allows one to mark appropriate events during tests.

The **light test** switch allows one to test the lights on the **driver's station** panel.

The **ramp control** switch raises and lowers the rear ramp.

The **control power on** light, which is on under normal operation, indicates that the control power bus is within a nominal range around 28 V dc.

The **computer power on** light, which is on under normal operation, indicates that the computer power bus is within a nominal range around 28 V dc.

The **checking for ground** light is on only when the computer is checking the 300 V dc bus for ground faults.

The **okay to start engine** light goes on after the 300 V dc bus has passed the ground fault test, and remains on until the engine is started.

The **checking systems** light goes on after the engine has started and remains on while the computer is checking various vehicle systems. This light goes off after the various tests have been passed.

The **all systems okay** light goes on when the tests indicated by the **checking systems** light are passed. This light goes off if a fault is detected within the vehicle.

The **warning** light will begin to blink if a warning class problem is detected. This will also cause a warning tone to sound in the driver's headphones.

The **fault** light will begin to blink if a fault class problem is detected. This will also cause a fault tone to sound in the driver's headphones.

A drawing of the DS panel is presented in Figure 31.
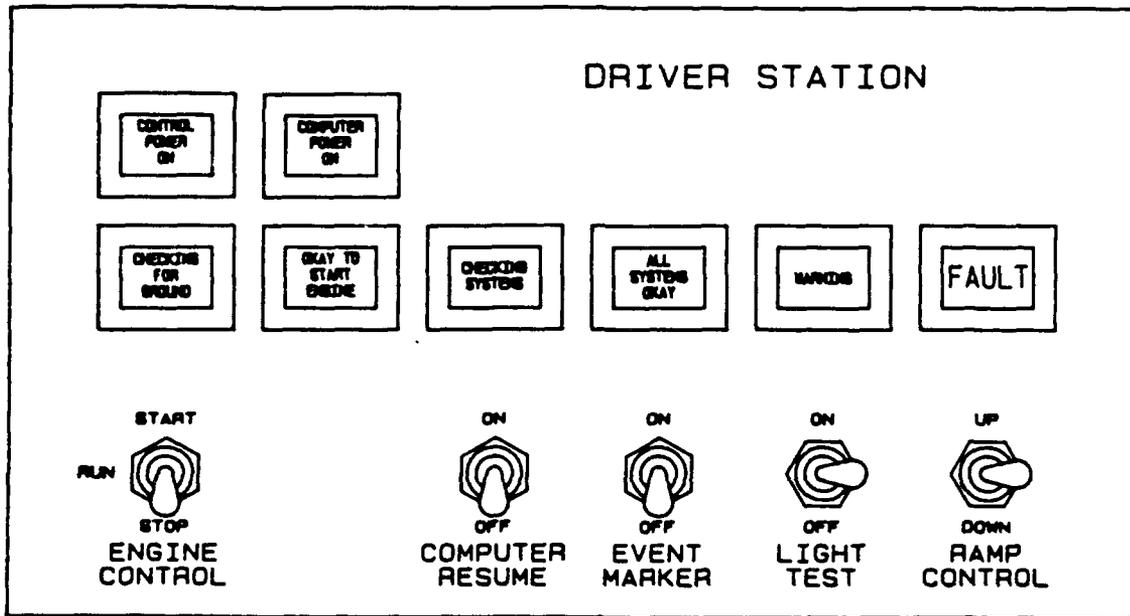
Figure 31. Driver's Station Panel

Section V

Control System Software

The control system software consists of ANABOX, CONTROL, and data processing programs. The ANABOX and CONTROL programs were developed by SwRI; the data processing programs were developed by SwRI, DTRC, and BRDEC.

ANABOX

This program was developed to emulate the solid state controls which were developed for the vehicle. In this program, the outputs—such as engine speed, motor speeds, and differential motor speeds—are a direct function of operator inputs.

CONTROL

The CONTROL program is based on the analytical equations for dc motors. The basic input is the accelerator which indicates desired speed. From this input, desired motor torques are computed; engine output is a function of both desired torques and auxiliary power requirements. The dc bus voltage (which is the armature voltage for both motors) is a function of desired motor speed which sets the proper field current for the ac alternators. Steering is dependent on having different field currents in the dc motors. The field currents are a function of desired motor speeds, which are different from side to side if a turn is desired.

Hydraulic braking is a function of the actual motor speeds versus the desired motor speeds when the desired speeds are less. The equations include proportional, derivative, and integral terms for smoother control but essentially it is the difference in actual versus desired speeds that is important. In the case of electrical braking, the dc bus voltage is set to zero, the braking grid is connected, and a deceleration rate is computed as a function of the difference between desired and actual speed. Then the deceleration torque is computed and the field currents are set accordingly.

DATA PROCESSING PROGRAMS

MILTOPE. This program was written by SwRI; it reads data from the various vehicle sensors and stores it onto the MILTOPE tape drive.

MILTOPE Tape Reading Program. This program was written by DTRC. This programs reads the data for each variable (M1 through M50) from the MILTOPE tape and stores that data on the Zenith hard disk drive. The filename is chosen by the user. Each data value is stored in a two byte or four byte character string. The size of each string depends on the variable length, which is determined by the specific variable.

MILTOPE Printing Program. This program was written by BRDEC. The purpose of the printing program is to take the file(s) created by the DTRC program, convert the character string data to numeric data, and perform various printing options using the data.

Section VI
Preliminary System Hardware Tests

ADAPTER GEAR TESTS

The purpose of the adapter gear tests was to assure proper performance and to determine efficiency before installation of the gears into the vehicle.

The adapter gears were found to be less efficient than originally thought. This low efficiency caused the oil in the original splash lubrication system to overheat, thus the splash lube system was changed to a forced lube system with two oil inputs and one oil scavenge per adapter gear (one gear for each dc motor).

FINAL DRIVE TESTS

To assure proper operation before installation, the FMC final drives (S/Ns 001 and 003) were tested at BRDEC.

The purpose of these tests was to determine the losses in the final drives, the proper functioning of the shifting, clutch, and brake systems, and the most effective design of the hydraulic system for the final drive and adapter gear. This was important in that it allowed for the correction of shortcomings in the final drive and adapter gear hydraulic system before installation into the M113.

Test Procedure. The final drive and motor/adapter gear were mounted onto a stable frame with the motor connected to a power supply. The angle of the motor in the test mount was the same as the mounting configuration in the vehicle; that is, the anti-drive end of the motor was tilted up 10 degrees. This mounting allowed for the fabrication of the motor brackets and mounts that would go into the vehicle and for the determination of the most effective method for aligning the motor to the final drive.

To determine the losses in the final drives, the inlet and outlet temperatures and flow rates of oil were measured. From this data, the amount of power lost by the final drives as heat was calculated. This test was done at final drive input speeds of 500 to 3,000 r/min.

To check the operation of the clutch, the solenoids for both low and high gear clutches were tested to insure that they controlled the clutch hydraulic pressure as required.

To check the operation of the brakes, a plot was made of the brake hydraulic pressure versus motor armature current (I_a) at a constant motor armature voltage (V_a) and motor speed. Using the formula, kW (braking power) = V_a ($I_a - I_o$), where I_o is the motor armature current with no braking applied, the amount of braking power applied at a given brake pressure could be calculated.

Results. The results of the final drive tests showed that they are not efficient in high gear at high speeds. For example, at the top input speed of 3,000 r/min, final drive #001 losses are about 54 hp and final drive #003 losses are about 47 hp. These are higher than expected and will reduce the top speed of the vehicle.

A graph of the losses in final drive #001 is presented in Figure 32. A graph of the losses in final drive #003 is presented in Figure 33.

The results of the clutch solenoid tests showed that they operated as expected.

The brakes were shown to be applying the proper stopping power, but their engagement time was much slower than expected. Upon examination of the brakes, it was found that the oil outlet orifice was too small to allow a quick release of brake pressure. This was fixed by enlarging the outlet orifice so that the engagement times could be brought to their proper quickness. *Remember that the brakes are energized as the brake pressure is reduced.*

MOTOR 247
ADAPTER GEAR #2
FINAL DRIVE #001-5

LOSS vs SPEED

LOSS (kW and HP)

kW   HP

40 — 54

30 — 40

20 — 27

10 — 13

0 —

0.0   0.5   1.0   1.5   2.0   2.5   3.0

FINAL DRIVE INPUT RPM (x1,000)

| 0 | 112 | 223 | 335 | 446 | 558 | 690 | (HIGH GEAR) |
| 0 | 48 | 96 | 143 | 191 | 238 | 286 | (LOW GEAR) |

SPROCKET RPM

——————— MOTOR & ADAPTER GEAR ONLY
— — — NEUTRAL
— — LOW
· · · · · · HIGH
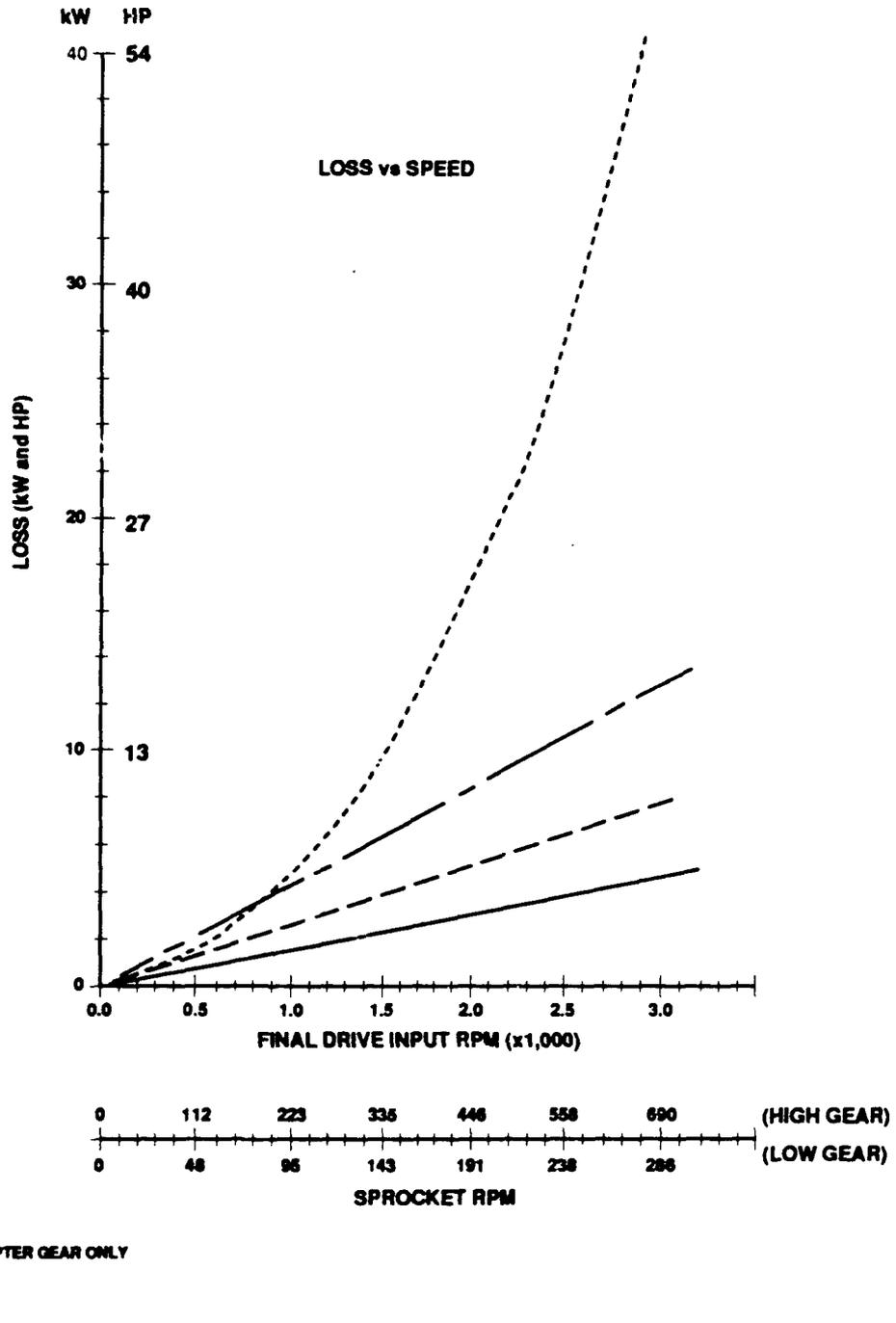
Figure 32. Graph of Losses in Final Drive #001
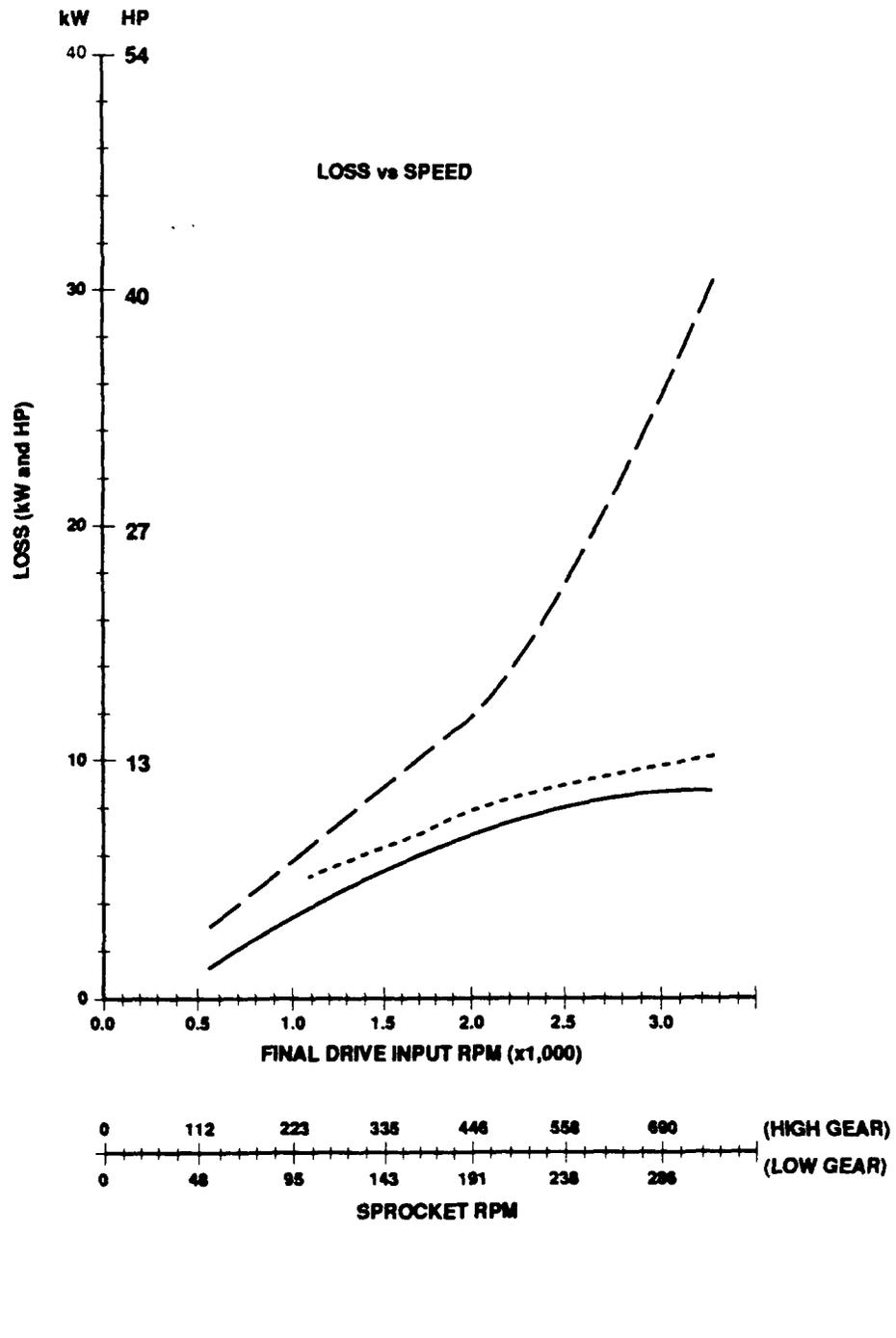
Figure 33. Graph of Losses in Final Drive #003

ENGINE ASSEMBLY TESTS

The purpose of these tests was to check the operation of the integrated engine assembly. The integrated engine assembly included the following components: Detroit Diesel engine model 6V-53T, Westech gearbox, Bendix dc generator model 30B95-3, both Bendix ac generators, Tyrone pump stack, Westinghouse POW-R-BRIK rectifiers model PIZ9A, BRDEC manufactured interphase transformer, and a load bank so power tests could be run. Data was gathered using a Hewlett Packard 3497A data acquisition unit.

The data acquisition unit recorded the following parameters:

- Time (data was printed out every 10 seconds)
- Engine shaft speed
- ac input control voltage for the Bendix ac generator control circuit
- dc field current for both Bendix generators (this parameter is the output of the ac generator control circuit)
- ac output voltage for both ac generators
- dc voltage across both rectifier bridges
- dc voltage across the interphase transformer
- dc current supplied by both rectifier bridges
- dc current supplied by the interphase transformer
- dc voltage across the interphase transformer
- Oil sump temperature (°F)
- Oil scavenge temperature for both ac generators

Systems that were checked during the tests included the alternator balancing circuit, the electrical balance of the Bendix ac alternators, Detroit Diesel engine horsepower output, hydraulic and cooling system, Westech gearbox losses, interphase transformers, Tyrone pump stack, alternator field control circuit, data transducers, efficiency and losses of the complete integrated system, and the ramp generator for engine governor control.

Difficulties. Problems were encountered with the following systems:

- Engine horsepower output
- Tyrone pump stack

The original engine used for the tests seemed to be putting out only 220 hp instead of the expected 290 hp. The engine was inspected by a Western Branch diesel engine technician, who suspected bad fuel injectors; these were replaced, but with no affect on engine performance.

It was then decided that the Marine Corps would provide a new dynamometer tested engine. The new engine performed satisfactorily on the dynamometer tests (putting out 296 hp at 2,800 r/min). When tested at BRDEC, the engine put out about 270 hp at 2,800 r/min. This was deemed sufficient performance.

The Tyrone pump stack is the ganged set of pumps run off the Westech gearbox. The stack has four inputs and outputs. It supplies hydraulic and cooling flow for the Bendix ac generators and scavenge for the ac generators and the Westech gearbox.

The original Tyrone pump stack was too long to fit into the engine compartment, and the one received to replace it rotated in the wrong direction. This reversed rotation was fixed with a new part from Tyrone.

SIMULATOR BOX TESTS

Before installing the SwRI computer control system, it was deemed advantageous to test the vehicle control hardware, using the simulator box supplied to Brdec by SwRI as part of the control system contract. This allowed for verifying the operation of the vehicle control hardware before the control computer was installed.

The simulator box consists of analog circuits designed to mimic the behavior of the control computer. The inputs to the simulator box consist of signals from the steering wheel, shifter, brake pedal, accelerator pedal, and the right and left dc motor armature currents. If the right or left armature current goes above a safe level, the simulator box will shut off the armature current to protect the dc motors. The simulator box only controls the vehicle drive system; it does not record data or display error messages as does the control computer. The simulator box can also be used as a backup in case of computer failure.

After some minor repairs, the simulator box was used to successfully test the control system wiring, relays, contactors, and circuits, thus assuring that the vehicle systems were operating correctly when the computer was installed. This test was done by driving the vehicle with the simulator box.

Section VII

Control System Integration—
Hardware and Software

The control system integration effort is described in Appendix C which gives a "running account" of the various difficulties encountered with and modifications made to the vehicle control software and hardware during the control system integration effort. Appendix C is by and large organized in chronological order.

Many tests were conducted to integrate the SwRI computer control system hardware and software with the M113 vehicle hardware and control circuits. These tests were first done with the engine assembly outside of the vehicle so that it would be more convenient (less noise, heat, etc.) for personnel to work. As the debugging and testing progressed, the engine assembly was installed into the vehicle and the appropriate sensors and control cables were connected. The stationary tests were the last tests done before preliminary field testing of the vehicle.

The first portion of the stationary tests consisted of performing initial checkouts on the control system from SwRI to assure that all of its components were operating correctly. This included testing of the analog to digital and frequency to digital input boards, the parallel input/output lines, and the pwm and digital to analog output boards. These components were successfully tested by SwRI with BRDEC assistance.

Most of the control software was debugged and tested with the vehicle by BRDEC. SwRI was unable to support this effort for some period of time but did provide assistance over the phone. BRDEC debugged the ANABOX program and integrated new functions to expand its capabilities. The BRDEC modified ANABOX program provides electric braking, spin and pivot turns, and two forward gears but lacks the capability of shifting on the run. Appendix D provides the listing of the modified ANABOX program and related software routines. The vehicle performed fairly well with this program. Following the development of this program, BRDEC moved on to the main goal of the software effort, development of the CONTROL program. Additional work is required to complete the development of the CONTROL program.

Section VIII
Lessons Learned and Discussions

INTRODUCTION

The purpose of this section is to summarize, at a component and system level, the various lessons learned in constructing the computer controlled electric drive demonstration vehicle (CCEDV). This project provided an opportunity to get first hand knowledge and experience with the issues involved in constructing a feasible CCEDV. The experience and knowledge gained will provide useful input to future projects undertaken in this area.

This section discusses the major areas of the project which caused difficulties and/or showed opportunity for significant improvement. Also included are discussions, at a component level, of how current technologies could be reasonably applied to the CCEDV.

FINAL DRIVES

In retrospect, it looks like the final drives were expected to do too much in a limited space, resulting in poor operation in many areas: these included excessive hydraulics, fluid leakage, and significant losses at high speeds.

For the sake of expediency, modified, off-the-shelf motors and existing final drives, which had been used in a previous vehicle, were selected for this project. Because of a speed mismatch between the motors and final drives, an adapter gear was inserted between them. The final drives are two speed planetary units; since it is possible to decouple the sprocket drives from the input, modulated brakes were added during the course of the project. The losses in the gearbox in high range at full speed are almost 50% because of the addition of the brakes. The hydraulic system for the final drives is completely external and required an extremely complicated installation.

HYDRAULIC SYSTEM

As it stands now, the hydraulic system is complicated, but it could be simplified significantly. There are 16 pumps, two kinds of oil, one cooler, and many hoses, valves, etc. The hydraulic needs of the final drives have caused a large portion of this complexity. There are seven hydraulic connections and at least two scavenge connections to each final drive. The drives require three different hydraulic pressure levels and a significant amount of cooling flow.

The scavenge lines do not remove the cooling fluid fast enough, and the resulting case pressure causes a leak through the sprocket shaft. One possible solution is to have the drives designed to operate while flooded (i.e., pressurized), so that a pressurized supply would move the oil through the drive to the sump without scavenge pumps.

Significant improvements can be made to the oil system for the alternators and gearbox; at present, there are four pumps in this system. The gearbox could be designed to drive and support the alternators in their original one-bearing configuration while letting the cooling oil drain into the gearbox without scavenge pumps. This could be done by redesigning the alternator scavenge paths or by using a pressurized housing like the one on the dc generator. Having the alternator housing pressurized would help to force oil out of the drive end into the gearbox.

The final drives could probably use the same oil as the alternators, which would help to simplify the hydraulic system further. A common oil has positive logistical implications.

PUMPS

There are inductors in series with some of the pump motors to limit excess starting current which could damage the shafts. There are also some large resistors in series with other pump motors to reduce the input voltage and thus slow the pumps down to the desired flow rate. Properly sized pumps and/or motors would have eliminated the need for the extra inductors, resistors, and their associated relays.

DC MOTOR ADAPTER GEARS

A significant improvement in the drive train can be accomplished by matching the final drive output shaft speeds to the motor optimum speed, thus eliminating the dc motor adapter gears and their attendant hydraulic needs (two supplies and a scavenge for each adapter gear).

ELECTRICAL MACHINES

This section discusses improvements and options for the electrical machinery used in the vehicle.

AC Generators. The generators performed very well. They are, however, oversized for this application. The engine power available is 149 kW and the generators total 225 kW. Their major drawback is that if they aren't turning fast enough to produce sufficient voltage for the power required, the rated current can be exceeded. Being aircraft-type generators, there isn't a lot of excess iron in the core, the saturation curves break very sharply at about 10 V over rated voltage, and there isn't a lot of overload voltage to play with. The saturation curve is very steep, making control of field current very sensitive. It is also necessary to run these machines close to rated speed to obtain rated voltage, which means there is less opportunity to operate at lower, more economical engine speeds. Their overload current capability is very good, however, and produced more than sufficient starting torque.

The worst problem in the generator system is the four-gang pump assembly used to supply and scavenge oil for the two generators. It leaks between stages and the generator cavities fill up with oil. Since these ac generators shouldn't be run with the cavities full, they have to be drained prior to operation.

In comparing air cooled machines with oil cooled machines, the ancillary equipment needed with oil cooled machines and the additional complications are often forgotten. There are high speed gearboxes, pressure pumps, scavenge pumps, plumbing, cooling devices (although in this application we used the transmission oil cooler on the engine), and extra power is required for these devices. Often these machines are for aircraft and are expensive. They don't have a great voltage overload capability since core size is kept to a minimum to save weight. These features should be kept in mind when selecting machines for vehicle applications. In general, when comparing an oil cooled machine with all it's auxiliary equipment to a comparable air cooled machine, it is not clear whether oil cooled is a better choice except that it can be used in a much more hostile environment.

DC Generator. The Bendix dc generator (30B95-3) is a self-contained, oil cooled unit that adds very little complication to the system. It is rated at 28V dc and 650 A, has self-contained pressure and scavenge pumps, and uses engine oil.

DC Motors. The dc motors also perform well. These motors have high starting torque and good overload current capabilities. The motors have been operated in the overspeed region from 5,200 to 6,000 r/min. There have not been any problems with the brushes and commutator. The motors are heavy (720 pounds each), but the main objective of this project was not to optimize the weight of the electric machine components but to demonstrate the electric drive vehicle performance with the digital control system using low risk, off-the-shelf components.

The decision to use an ac or dc drive system is not an easy one today; each system seems to have its own advantages and disadvantages. In the dc drive system, controlling the motor speed is simple; the speed can be controlled by either controlling the armature voltage or the field current, or both (as in our case). The dc motor performance, however, is limited by the mechanical commutator and brushes. The ac motor, on the other hand, is mechanically robust and light weight. The ac motor, however, usually requires control of voltage, current, and frequency in order to meet the torque-speed duty cycle of a drive system. The required power electronics for the ac drive system can be relatively complex, and closed loop control is normally required with complete analysis and simulation of the entire drive. Also, the dynamic behavior of an ac motor, such as an induction motor, is more complex than that of a dc motor.

The continuing advances in the development of the power semiconductor and microprocessor technologies greatly improve the application of power electronics in electric drive systems. This seems to make an ac drive system a more serious competitor than a dc drive system. There are two main classes of ac machines: induction and synchronous machines. The induction machines have been used in related electric vehicle propulsion R&D efforts for military vehicle applications and in electric cars by industry. In recent years, the development of high energy permanent magnet (PM) materials, such as neodymium-iron-boron and samarium cobalt, have introduced new possibilities for the applications of PM synchronous motors in ac variable speed (electric drive) applications. In these machines, the field excitation is provided by PM in the rotor eliminating the need for a dc power supply and a field coil. The stator of these machines is similar to that of a conventional synchronous machine with the three-phase winding supplied from a variable frequency inverter power source. The machine speed can be controlled to be in synchronism

at all values of the stator or inverter frequency by a shaft position sensor. The model of the PM synchronous machine can be obtained from its analogy to the conventional wound field synchronous motor using the d-q Park transformation technique. When this model is established, the vector control technique (controlling both the magnitude and phase of the control variable) can be used to convert the PM synchronous machine to an equivalent separately excited dc machine, which has desirable control characteristics. For example, if the direct-axis stator current is reduced to 0, i.e., the angle between the stator magnetomotive force (mmf) and the magnet axis is 90 degrees, then the machine torque equation is reduced to:

$$T = K\, i(q)$$

where

K = $P/2\, \lambda\, (m)$
P = numbers of poles
$\lambda\,(m)$ = flux linkage due to the rotor magnets linking the stator
$i(q)$ = quadrature-axis stator current

This torque equation is similar to that of a separately excited dc machine. This equation also represents the maximum torque of the PM machine. The PM machine maximum torque is limited by protection of the magnet from demagnetization, and saturation of the stator iron. To operate the motor in the overspeed (constant power) region, the angle between the stator mmf and magnet axis is varied over the range from 90 to 180 degrees. In this condition, the stator current, i(d), opposes the magnet's mmf. This, in turn, reduces the net air gap flux, similar to the field weakening approach used in dc drives. There are many papers in the literature on the design, modeling, simulation, and analysis of variable speed PM synchronous machines.

POWER ELECTRONICS

The rectifiers and transistors are Powerex modules where electrical ports are isolated from the heat port. This makes it possible to heat sink the devices on the aluminum hull of the vehicle without the usual problems of electrical isolation. However, the outside of the hull heats up where these devices are mounted and, if infrared signature were of concern, it would probably be better to mount these devices on the floor of the vehicle. It would probably be wise to machine the mounting areas to meet the flatness and surface finish specifications to assure the best heat transfer possible.

The development of the motor field current controllers presented a very challenging task. Developing snubber circuits for the power transistors was difficult in that no theoretical approach seemed to work. A more empirical approach was eventually taken which produced the existing snubber circuits.

There were frequent transistor failures during vehicle testing. The field circuits were analyzed to determine the cause(s) of the failures. The work to date indicates a number of potential problems in the existing circuits:

- A more effective snubber circuit would reduce the transistor switching losses and protect the transistor from second breakdown. Second breakdown is the breakdown of the transistor junction due to localized heating effect during switching; it is a common cause for frequent transistor failure. Hence, it is important that the snubber be carefully designed to protect the transistor. The first snubber resistor was a standard wire wound type resistor which is inductive. This resistor would generate its own voltage spike, defeating the purpose of the snubber circuit. This resistor was replaced with a non-inductive winding type resistor.

- The existing snubber capacitor of 2,700 micro-Farad is large. In general, a large snubber capacitor reduces the peak voltage and dv/dt across the transistor at turn-off but increases the snubber loss. The capacitor value should be optimized to provide better performance.

- The transistor turn-off time in the existing circuit was measured to be about 125 micro-seconds with a collector current of about 70 A. This turn-off time is long and can cause high turn-off dissipation. On the other hand, the turn-on time was measured at about .5 micro-seconds. An application engineer at Powerex (the transistor manufacturer) advised that the turn-off time for our circuit should be about 30 micro-seconds, and that the lengthy turn-off time could be our biggest problem.

- The freewheeling diode across the motor field should be a fast recovery diode. The existing circuit uses a standard recovery type diode.

- With the vehicle electrical system operating (i.e., engine-on) voltage spikes exist on the collector voltage waveform. The frequency of these spikes is at the field controller pwm switching frequency (500 Hz). The maximum voltage spike recorded was about 80 V at about 100 A collector current. The impact of this on the transistor has yet to be determined; 80 V is within the maximum rated collector voltage of 450 V, but the collector current waveform also needs to be looked at.

The fast recovery diode is on order. The snubber resistor was recently replaced with a new noninductive resistor of the same value. The result was dramatic with the transistor turn-off time reduced to about 25 micro-seconds. This is a step in the right direction.

The near term future plan is to simultaneously observe the transistor voltage and current waveforms and then to plot the peak power dissipation at turn-on and turn-off. The objective of this test is to check if the transistor is operating in the safe operating area (SOA) both in the forward and reversed biased condition. Additionally, the transistor snubber circuit will be redesigned.

AC GENERATOR FIELD CURRENT CONTROLLERS

The original idea was to provide an analog signal (0 to 5 V) to a closed loop controller that would supply a regulated field current to each alternator, with the level of the alternator voltage output dependent on field current input level. In retrospect, this may not have been the proper way to accomplish the desired result. The end objective is to control the level of the dc motor voltage bus. It may have been incorrect to assume that there is a known and fixed relationship between the alternator field current and the dc bus voltage because:

- The two alternators do not have the exact same saturation curves.
- The two curves may change individually with temperature.

One serious problem is the very large slope of the saturation curves in the required operating range. Thus, a small change in field current creates a large change in output voltage. A better approach would be to control the alternator output voltage with a controllable output voltage regulator for each alternator, and use the computer to set the desired alternator voltage levels. That is, have the regulator directly control the alternator voltage, rather than separately controlling the field current to get the desired voltage. Thus, the feedback to the regulator would be the alternator output voltage and not the field current level. In order to provide equal outputs from both alternators, one control signal from the computer would be sent to both regulators. This would provide a more linear control with a broader operating range.

CONTACTORS

The contactors used to connect the motor armature circuits to the 300 V dc bus are military standard three-phase contactors, with the phases paralleled to increase current capability.

To make a pivot turn, it is necessary to disconnect the inside motor because that motor becomes a short circuit when it is stopped. The ANABOX control software originally disconnected the contactors under high current. These contactors are ac type and aren't designed to withstand this abuse. Several contactor failures were experienced. It is alternately possible to set the bus voltage to zero with software prior to starting the turn, open the contactor, and then restore the voltage after the current drops. This scheme was implemented in the software later. More testing is required to determine how well this works in terms of drivability. The disadvantage of this scheme is that it degrades drivability since there is a lurch prior to starting the turn.

A possible hardware solution is to use transistors instead of contactors. Powerex has a 600 A transistor that, when paralleled, would handle the necessary current, although the drive and control circuit would require some engineering. This would yield direct control of the armature circuit if we included a pwm scheme and could provide more precise control of the vehicle.

WIRING/GROUNDING SYSTEM

Significant improvements in the wiring system could be made by eliminating analog control signals where possible and using digital control throughout the vehicle instead. Digital controllers for the governor and the motor and alternator field controls are feasible. Fiber optic cable could be used to carry digital signals directly from the SC-1 computer to the various controllers. Fiber optic cables provide better isolation because of their immunity to electrical interference. This would also eliminate the D/A cards which were installed on the SC-1.

ELECTRICAL NOISE

The vehicle power, control, and drive systems contain many probable sources of interference: drive motor commutators, power relays, control relays, rheostats, switching power supplies, power rectifiers, solid state pwm generator and motor field current controllers. Efforts were made to minimize these interferences through various interference control schemes described in Section II.

The four electrical power systems on the vehicle are completely isolated from each other. There are a number of isolated power supplies for the computer and feedback sensors. A lot of effort went into eliminating ground loops to help reduce noise.

In retrospect, it may be better to power the pwm current field controllers from a separate power supply instead of the 28 V dc control bus. The motor field current controllers pulse up to 165 A dc each off this bus and the noise from this current permeates not only the 28 V dc system but the isolated supplies for the computer and sensor system as well. Having the computer control signal returns connected to the D/A power supply return did not help this situation. However, it is not believed that this noise caused any detrimental effect to the vehicle control systems. Filter circuits and software averaging routines helped.

COMPUTER CONTROL SYSTEM

The computer used in the BRDEC electric drive vehicle, the SC-1, is a very good one which is normally used in space vehicle applications. It is a very well constructed computer which is protected against shock, vibration, and impact. It is based on the Intel 8086 and has an 8087 math processor and an 8089 for communications.

An off-the-shelf modular computer for development projects might be better for this application. They are much cheaper, the variety of different types of insert boards (A/D, D/A, Digital I/O, etc.) provides the opportunity for a variety of system topologies, and spare parts are readily available. Maintenance could be simplified. One very effective, albeit unsophisticated, method of troubleshooting a malfunctioning computer is to just change boards and ship the broken board back to the manufacturer for repair or exchange.

Another advantage of the modern modular computers is that they come with sufficient documentation to understand the machine and eliminate guesswork. The address maps, board configurations, and input and output conventions are all well explained. They also usually can be obtained with software that provides some simple commands for manipulating the computer; this is useful in getting started, in running other software, and even in troubleshooting.

There are disadvantages as well. A tracked vehicle is a very abusive environment. There are temperature extremes, shock, and vibration to contend with. Electrical noise is also a problem, depending on what systems are present, as is the degree of electrical isolation. An industrial computer for a vehicle would need some modification to withstand the rigors of this application, but it would certainly cost less than a spacecraft computer.

SOFTWARE DEVELOPMENT

The basic software scheme for the electric drive vehicle consists of two superimposed loops which run alternately. The inner loop, which runs every 30 ms and is interrupt timed, contains the most important algorithms; all critical inputs are measured in this loop and desired motor and generator field currents and engine speed computed. The outer loop runs in slices when the inner loop isn't running and takes a total of 120 ms to run. It contains parameters which are less important and don't critically affect the operation of the vehicle in the short term. Temperatures, data output, and even some operator inputs are included in this loop. It seems like a mistake to include operator inputs in the slower loop but, in reality, there are no apparent lags since 120 ms is below the threshold of comprehension.

The software concepts for this vehicle, formulated between 1982 and 1984, have roots which go back even farther to previous hydraulic vehicles. Computer systems have come a long way since then and the system could be improved with distributed processing much the way automobiles are progressing. One method of distributed processing would contain one processor for the engine (electronically controlled diesels have arrived) and generators, another for the motors and final drives, or perhaps even one for each side, and another processor for overall system control. This has the advantage of quicker response but, more important since poor response was never an insurmountable problem, it breaks the software into smaller units which should facilitate writing and troubleshooting. Communication between computer boards could be via a backplane bus, RS-232 connection, or fiber optics.

Much of the software in this program is standard. Reading A/D boards, writing to D/A and frequency boards, setting, clearing, and testing bits in output and input words are not much different than other applications.

In other areas, standard approaches to software did not work as well. A computer responds much faster than a 14-ton tracked vehicle and this was a source of trouble in many cases.

Armature currents and dc bus current are the best examples of this type of problem. The commutator on a dc motor is nothing more than a many segmented switch, 24 in the Mawdsley motors in this vehicle. The average current going into the armature is desired as a parameter. But a computer A/D board usually measures and completes the conversion in about 25 μs. Armature current varies wildly in its own time frame because of the commutator switching. The resulting data goes from one extreme to the other very quickly although the average value is quite reasonable. But a measurement that only takes one 25 μs time slice can be grossly unrepresentative of the average and represent the extremes instead.

To make matters even worse, many computed values are functions of armature current and they all have the same fluctuations and contribute to the instability of the system. Averaging routines and filtering of the inputs are needed.

Low pass filters alone work very well in the case of field current input from the pwm (500 Hz) field controllers. It was not feasible to add filters to the armature and dc bus current inputs because it would have required extensive changes to the external wiring. Instead, a running average routine, borrowed from the Wall Street folks, was implemented. This worked moderately well. A simpler averaging routine was suggested by Mr. Stecklein of SwRI. It consists of taking the last value of the variable, multiplying by 19, adding the current value, and dividing by 20.

It appears that many of the internal variables in the program need averaging. A 14-ton vehicle provides a lot of damping and variables that vary much more quickly than its response time are not a particular problem. Other variables vary much more slowly, closer to the response time of the vehicle, and cause instabilities which affect the operation of the vehicle.

The outputs from the computer are all open loop in the sense that they aren't adjusted by the computer to be exactly wh t is requested. The various field controllers, engine governor, etc., are closed loop between the controller and device. For example, if 2,000 r/min is requested from the engine, the engine produces a speed that is as accurate as the signal it receives. It is a matter of adjustment and normally is quite acceptable. However, if the engine is loaded beyond the capability of the governor to compensate, the computer does not readjust the governor signal and the engine bogs down. The same is true of motor speeds. There are no readjustments of field and armature voltages to set the actual speed to the desired speed. The original plan which was not implemented called for a totally closed loop control system. The control system would monitor the difference between actual and desired speed and act to reduce the difference to zero, either by accelerating or decelerating. The difference between actual and desired speed would determine the rate of change which the control system would attempt. Of course, a totally closed loop system would be better and would give more precise control and better performance; it is one of the arguments for multiple processors.

DATA REDUCTION AND ANALYSIS

One of the most difficult problems to deal with on this project is a data system which doesn't work well. It caused major delays in the program because troubleshooting was frequently an exercise in intuition or often blind guesswork. For a developmental system, it would be better to dedicate a separate computer board to data alone so that any variable could be printed to both a screen (for instantaneous diagnosis) and a printer as well (to preserve a written record for later viewing). This would also make it easier to change the ratio of program cycles to data output. It is possible to miss important trends in a complicated system by having the wrong frequency of data. Any time spent on developing a good data system would probably be more than made up for during the troubleshooting phase.

Section IX
Conclusions and Recommendations

BRDEC hopes that this report provides helpful information to guide the further electric drive technology development needed to realize potential improvements in performance. The thrust of this project was to use off-the-shelf technology, low risk components, and digital control in an electric drive design that would meet the Marine Corps goals for performance, weight, and low space claim at a moderate cost.

Considerable engineering effort was placed in the design of the vehicle electrical power systems, power electronics, final drive hydraulic systems, and control scheme. The electric vehicle works with the digital control system but it doesn't work as well as originally expected.

Simplicity is an important consideration in the construction and operation of the electric drive vehicle. Anything that can be done to simplify, eliminate, or reduce the number of systems is worth pursuing. Self-contained modularization is one valid approach. It means complicated subsystems can be treated as a unit and just replaced when faulty. It is hard to move forward if all one's energy is used just keeping the system working.

The final drives, adapter gears, and associated hydraulic systems can be replaced with a compact motor/drive assembly that has the following features:

- High speed motors to reduce size per horsepower
- Self-contained modules where possible
- Torque/speed characteristics that eliminate the need for a gearshift.

The control system hardware and software development effort should interact as closely as possible. System integration is a critical issue.

A dedicated data acquisition system is a good idea. Distributed processing would facilitate software writing and troubleshooting.

The on-going developments in computers, electrical machines, and power electronics are quite positive. Vehicular applications of computers are today's technology. Matching the parameters of voltage, current, speed and torque are critically important.

Appendix A
Computer Inputs

COMPUTER INPUTS

SHEET 1 of 4

Magnetic Pickups

MP-1   Magnetic pickup for R-final drive input speed

MP-2   Magnetic pickup for R-final drive output speed

MP-3   Magnetic pickup for L-final drive input speed

MP-4   Magnetic pickup for L-final drive output speed

MP-5   Magnetic pickup for engine speed

Pressure Switches

PS-1   Pressure switch for gearbox pressure (5 lb/in^2)

PS-2   Pressure switch for ac generator pressure (5 lb/in^2)

PS-3   Pressure switch for dc generator pressure (5 lb/in^2)

PS-4   Pressure switch for ac generator-1 scavenge pressure (5 lb/in^2)

PS-5   Pressure switch for ac generator-2 scavenge pressure (5 lb/in^2)

PS-6   Pressure switch for engine lubrication system (5 lb/in^2)

PS-7   Pressure switch for engine fan motor pressure (500 lb/in^2)

PS-8   Pressure switch for brake and clutch supply (100 lb/in^2)

PS-9   Pressure switch for R-final drive scavenge pressure (5 lb/in^2)

PS-10   Pressure switch for L-final drive scavenge pressure (5 lb/in^2)

PS-11   Pressure switch for R-final drive LO clutch pressure (50 lb/in^2)

PS-12   Pressure switch for R-final drive HI clutch pressure (50 lb/in^2)

PS-13   Pressure switch for L-final drive LO clutch pressure (50 lb/in^2)

PS-14   Pressure switch for L-final drive HI clutch pressure (50 lb/in^2)

NOTE: All pressure switches, 0.0 volts with respect to control system ground
        corresponds to a pressure below the trip point while 27.5 volts corresponds
        to a pressure at or above the trip point.

A-1

Pressure Transducers

PX-1   Pressure transducer for R-final drive brake pressure $(0-5V=0-300 \text{ lb/in}^2)$

PX-2   Pressure transducer for L-final drive brake pressure $(0-5V=0-300 \text{ lb/in}^2)$

PX-3*   Pressure transducer for Brake Supply pressure $(0-5V=0-300 \text{ lb/in}^2)$

Current Transducers

VX-1** Current transducer connected to measure dc bus voltage $(0-5V = 0-300V)$

VX-2   Current transducer connected to measure R-Motor armature voltage
        $(0-5V = 0-30V)$

VX-3   Current transducer connected to measure L-Motor armature voltage
        $(0-5V = 0-30V)$

VX-4   Current transducer connected to measure R-Motor field voltage
        $(0-5V = 0-30V)$

VX-5   Current transducer connected to measure L-Motor field voltage
        $(0-5V = 0-30V)$

VX-6   Current transducer connected to measure R-Motor compensating windings
        voltage $(0-5V = 0-10V)$

VX-7   Current transducer connected to measure L-Motor compensating windings
        voltage $(0-5V = 0-10V)$

CX-1   Current transducer for dc bus current $(0-5V = 0-2000A)$

CX-2   Current transducer for R-Motor armature current $(0-5V = 0-1000A)$

CX-3   Current transducer for L-Motor armature current $(0-5V = 0-1000A)$

CX-4   Current transducer for R-Motor field current $(0-5V = 0-250A)$

CX-5   Current transducer for L-Motor field current $(0-5V = 0-250A)$

CX-6   Current transducer for ac generator-1 field current $(0-5V = 0-5A)$

CX-7   Current transducer for ac generator-2 field current $(0-5V = 0-5A)$

*   Comes into main junction box and the engineer's station but does not
    go to computer.

** This transducer also has windings through window for use with the ground
    check system.

A-2

Operator Controls

AC-1   Accelerator control - 0 to 5.0V dc proportional to desired speed

BC-1   Brake control - 0 to 5.0V dc proportional to desired braking

DC-1   Directional steering control - 0 to 5.0V dc proportional to desired
       turning angle

RC-1   Engine run control - signal is high when the operator desires the
       engine to run   (high = 5.0V dc with respect to control system ground)

GS-1   Gear Selector - shaft encoder that outputs an 8 bit gray code identifying
       one of six possible shifter positions

CR-1   Computer Resume - a momentary high (high = 5.0V dc with respect to system
       ground) will cause the computer to continue operating from the sequence
       hold

EM-1   Event Marker - a momentary high (high = 5.0V dc with respect to system
       ground) will cause the computer to output a marking signal to the
       MILTOPE recorder

Other Inputs

EC-1   Engine crank control - signal is high when starter is engaged
       (high = 5.0V dc with respect to control system ground)

Thermocouples

TX-1   MIL-L-2104 Lubricant Sump

TX-2   MIL-L-23699 Lubricant Sump

TX-3   ac generator-1 scavenge oil

TX-4   ac generator-2 scavenge oil

TX-5   dc generator scavenge oil

TX-6   Gearbox scavenge oil

TX-7   Right final drive scavenge oil

TX-8   Left final drive scavenge oil

Thermocouples (continued)

TX-9   Engine coolant

TX-10   Engine oil

TX-11   Engine exhaust

TX-12   Engine intake air

Appendix B

Computer Outputs

Digital Outputs

Digital control signals are defined to be low whenever the voltage is less than 0.4 volts (nominally 0.0 volts) and high whenever the voltage is over 4.0 volts (nominally 5.0 volts).

SS-1   This signal appears immediately following computer self-check. It goes low to energize a relay used for ground fault checks. The signal stays low until all ground fault checks are satisfactory.

SS-2   This signal goes low when the engine run switch is in "RUN" (RC-1 goes high) and the ground fault checks are passed. It is used to permit engine cranking. It remains low until the engine speed reaches 300 r/min or until cranking has continued for 30 seconds.

SS-3   This signal goes low when SS-2 goes low. It is used to energize the fuel solenoids and stays low until the computer decides to stop the engine, or the timer interrupts cranking.

SS-4   This signal goes low when the pressure switches PS-1 thru PS-7 have closed. The signal is used to energize the final drive pumps and remains low until the computer is signaled to shut the system down (RC-1 goes low).

SS-5   This signal is to be low anytime it is desired to have the R-Motor armature connected to the dc bus. Whenever this signal is not low, the R-Motor is disconnected.

SS-6   This signal is to be low anytime it is desired to have the L-Motor armature connected to the dc bus. Whenever this signal is not low, the L-Motor is disconnected.

Digital Outputs (continued)

SS-7   This signal is to be low anytime it is desired to have the R-Motor
        field set for forward motor rotation.

SS-8   This signal is to be low anytime it is desired to have the R-Motor
        field set for reverse motor rotation.

        If both SS-7 and SS-8 are not low, the R-Motor field is disconnected.
        If both SS-7 and SS-8 are low, the field is connected; the direction
        of the connection depends on which signal appeared first; the coils
        on the switch may overheat and burn out over a long time.

SS-9   This signal is to be low anytime it is desired to have the L-Motor
        field set for forward rotation.

SS-10   This signal is to be low anytime it is desired to have the L-Motor
        field set for reverse rotation.

        If both SS-9 and SS-10 are not low, the L-Motor field is disconnected.
        If both SS-9 and SS-10 are low, the field is connected; the direction
        of the connection depends on which signal appeared first; the coils
        on the switch may overheat and burn out over a long time.

SS-11   This signal is to be low anytime it is desired to connect the braking
        resistor to the dc bus. Whenever this signal is not low, the braking
        resistor is disconnected.

B-2

Digital Outputs (continued)

SS-12   This signal is low anytime the engine speed is above 300 r/min.

SS-13   This signal is to be low anytime it is desired to engage the right
        final drive low clutch.

SS-14   This signal is to be low anytime it is desired to engage the left
        final drive low clutch.

SS-15   This signal is to be low anytime it is desired to engage the right
        final drive high clutch.

SS-16   This signal is to be low anytime it is desired to engage the left
        final drive high clutch.

        If both SS-13 and SS-15 are not low, the right final drive is in neutral.
        If both SS-13 and SS-15 are low, we are not sure which clutch will be
        engaged, however, both clutches can not engage at the same time.

        If both SS-14 and SS-16 are not low, the left final drive is in neutral.
        If both SS-14 and SS-16 are low, we are not sure which clutch will be
        engaged, however, both clutches can not engage at the same time.

SS-17   This signal goes low and stays low anytime SS-5 thru SS-10 are high.

SS-18   This signal goes low anytime either motor field resistance exceeds
        0.180 ohms and remains low until both field resistances are below 0.170
        ohms.

Digital Outputs (continued)

SS-19   This signal goes low anytime the Right Brake is being applied and
         remains low until the brake is released.

SS-20   This signal goes low anytime the Left Brake is being applied and
         remains low until the brake is released.

SS-21   Not used.

SS-22   Not used - However, the SS-22 relay is used to operate DS-2 (computer
         power on) light.

SS-23   This signal goes low and stays low as long as the "ground check"
         is being performed and there is no fault (operates DS-3).

SS-24   This signal goes low when SS-23 goes not low following the "ground
         check". It stays low until the engine is started (operates DS-4).

SS-25   This signal goes low when engine is above 300 r/min and stays low
         until all system checks are satisfactory (operates DS-5).

SS-26   This signal goes low when SS-25 goes low following successful
         completion of system checks (operates DS-6).

SS-27   This signal goes low when computer detects a fault (operates DS-7).

SS-28   This signal goes low when the computer detects an output of limit
         parameter that does not require an automatic shut down (operates DS-8).

SS-29   Not used

SS-30   Not used

SS-31   Not used

SS-32   Not used

B-4

Pulse Width Modulation (pwm) Outputs

BS-1   24 V pwm output proportional to the desired braking for right final
        drive brake, with 0% duty cycle corresponding to maximum braking (minimum
        brake pressure) and 100% duty cycle corresponding to minimum braking
        (maximum brake pressure).

BS-2   24 V pwm output proportional to the desired braking for left final
        drive brake, with 0% duty cycle corresponding to maximum braking (minimum
        brake pressure) and 100% duty cycle corresponding to minimum braking
        (maximum brake pressure).

Analog Outputs

EG-1   Voltage output proportional to the desired engine speed, with 0.0 volts
        corresponding to 700 r/min and 5.0 volts corresponding to 2800 r/min.

FC-1   Voltage output proportional to the desired right motor field current with
        0.0 volts corresponding to 0.0 amps and 5.0 volts corresponding to 165 amps.

FC-2   Voltage output proportional to the desired left motor field current with
        0.0 volts corresponding to 0.0 amps and 5.0 volts corresponding to 165 amps.

FC-3   Voltage output proportional to the desired alternator field current
        with 0.0 volts corresponding to 0.0 amps and 5.0 volts corresponding to 4.0
        amps.

Appendix C
Control System Integration Account

A. INITIAL ROUTINE DEBUGGING

The first portion of the control program to be tested was the initialization (INITIAL) routine. This routine performs the ground fault check and various tests on different vehicle systems to assure that the hardware is working properly and that the vehicle can be safely started. Testing and debugging of this routine precipitated several problems with the vehicle hardware and the digital control system which are described in proceeding sections.

Soon after receiving the control software from SwRI in January of 1989, BRDEC acquired the capability to perform in-house modifications to the SwRI code. The FORTRAN code development software, FORTRAN-86 compiler, which was compatible with the FORTRAN used by SWRI, was acquired. Daniel Lewis from the Information Systems Division of BRDEC was instrumental during the early stages of the software modification effort.

In the first in-house review of the SwRI ANABOX code, many errors were discovered which prevented the code from compiling. Mr. Lewis was able to correct these errors.

B. GROUND LOOP

The original plan was to have a two wire circuit, one for the control voltage signal and one for signal return, for each of the four analog control signals coming from the SC-1 D/A boards. It turned out that the signal return connections were not provided on the D/A boards although the connectors of the D/A boards contained the signal return wires. Since it was not desired to have the signal returns in a floating mode, all signal returns were connected to the control power return terminal. This created ground loops between the analog outputs of the computer and the field controller outputs. This situation is shown in Figure C-1 and indicates that the ground for the control signal from the field current controllers had an improper path back to its power source through the computer control output lines. These ground loops placed a great deal of electrical noise onto the returning control signals, and this noisy signal was in turn being fed back through the analog boards to the field controllers, causing a feedback effect. Erroneous signals appeared at the ac generators and dc motor field current controller inputs which in turn caused the controllers to output improper field currents to the generators and motors. This problem was solved by breaking the improper control signal ground path as shown in Figure C-2. But the disadvantage of this rewiring was that the signal returns are common to the ±15 V dc switching power supply that powers the two D/A boards.
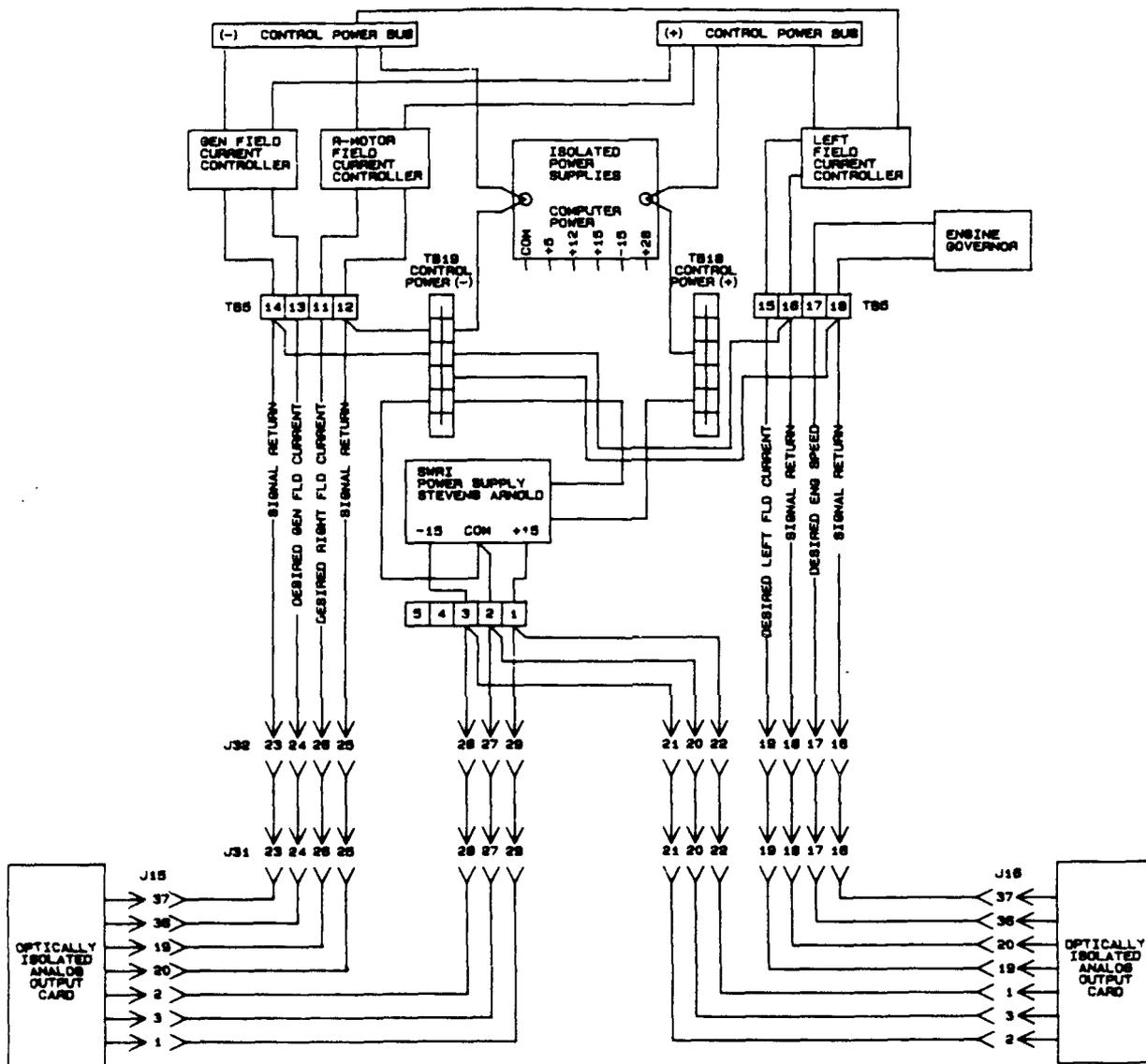
Figure C-1. Control Wiring Diagram with Ground Loop
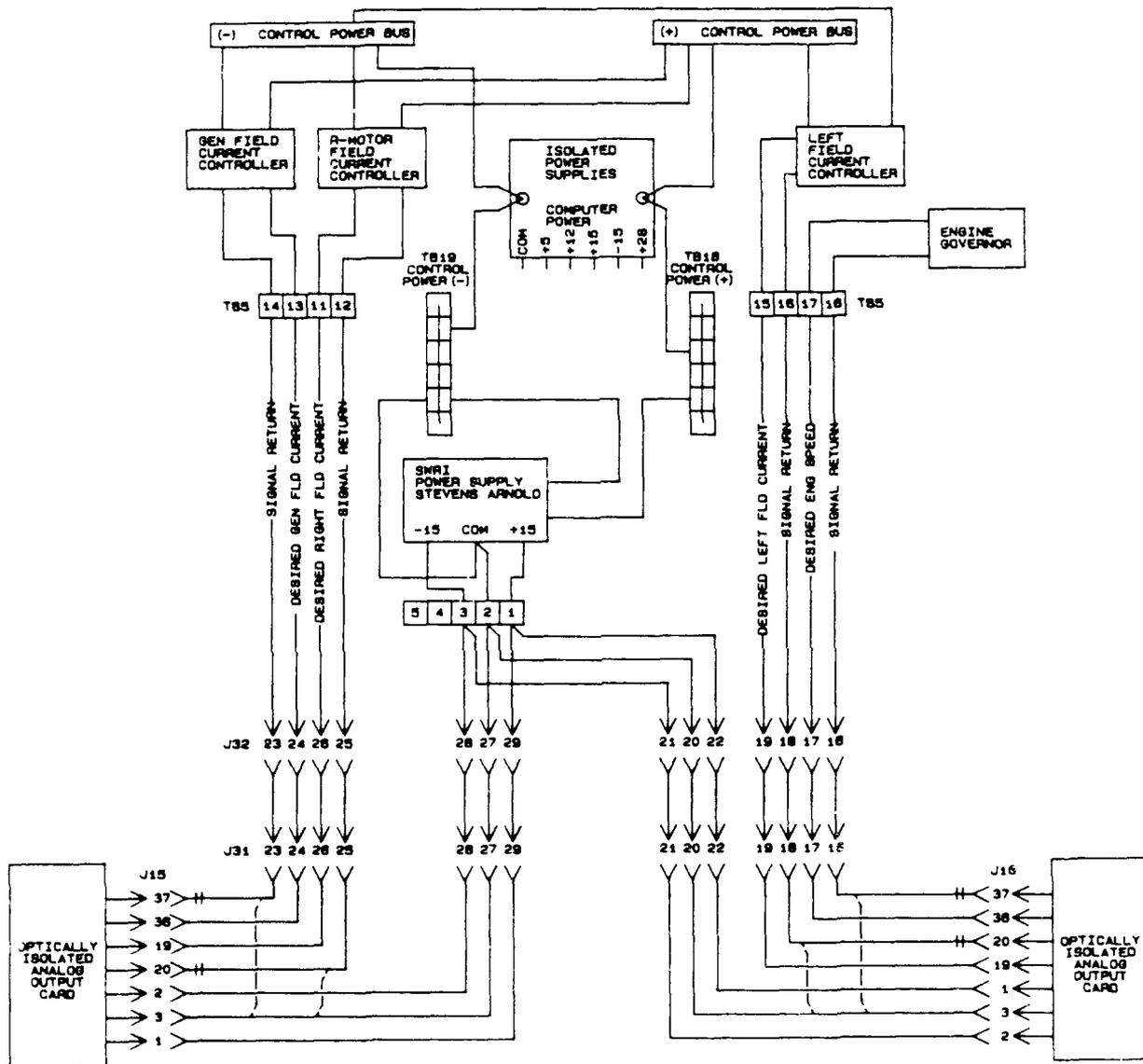
Figure C-2. Control Wiring Diagram without Ground Loop

C. FIELD CURRENT CONTROLLER DEBUGGING

As testing the INITIAL routine progressed, it soon became apparent that the circuit which controls the field current to the motors was not working properly; it was not delivering the expected field current values for a given input signal. It was discovered that there was excessive noise in the circuit due to the large currents being switched quickly; the circuit was modified to help reduce this noise.

It was also determined that one of the MOSFETs which controlled the base current to one of the main motor field controller transistors (Darlington transistor) was damaged. This MOSFET was causing the transistor to operate in the active region instead of the saturation region, and this was causing the transistor to experience excessive and damaging current heating. This MOSFET was replaced. The Darlington transistors were also experiencing excessive dV/dt across the collector to emitter junction due to inadequate snubber circuit across this junction. A more efficient snubber circuit was designed and installed across the junction.

D. ENGINE COOLING FAN PRESSURE SWITCH

During debugging of the INITIAL routine in the SwRI code, it was discovered that the engine cooling fan hydraulic pressure was not high enough to close the engine fan pressure switch #2 (PS-2). This problem caused the INITIAL routine to prevent the engine from going past idle speed (700 r/min) because the routine checks to see if this switch is closed. This problem was solved by ordering and installing a pressure switch with a lower trip point.

E. "NOISE" PROBLEMS

It was discovered that when a dc voltage from a standard cell battery was applied at the input to the #2 generator A/D board, this data, when looked at from the MILTOPE, had a "noise" bandwidth of about 13%. This seemed to indicate that the SwRI computer or the A/D board was interpreting a steady dc signal as having noise or fluctuations.

This was a problem because one of the tests done by the INITIAL routine checks the bandwidths of the transducer signals to see if they fall within an acceptable range. It was thought that if the bandwidth was excessive, the computer would not be able to properly control the vehicle; that is, the computer needs a fairly accurate reading of the various vehicle data for the control algorithms to work. Excessive bandwidth could create unsteady or unstable operation.

It was thought that perhaps one or some of the switching power supplies in the system was creating this noise. These supplies were successively removed from the computer circuit with no reduction in the noise.

It was then decided to perform some more extensive tests to help quantify the noise problem. The dc switching power supplies were replaced with batteries and the data from the traction motor and alternator field currents were observed and analyzed. The table below details the results of these tests.

	USING BATTERIES			USING POWER SUPPLIES		
Signal Source	Band-width (%)	Chebyshev Deviation (%)	Standard Deviation (%)	Band-width (%)	Chebyshev Deviation (%)	Standard Deviation (%)
RMFC	11.6	0.9	1.3	10.8	1.0	1.3
LMFC	8.9	1.1	1.3	7.8	1.3	1.5
G1FC	16.4	2.1	2.7	8.6	2.2	2.5
G2FC	11.2	2.2	2.5	9.2	1.0	1.2

RMFC = Right Motor Field current
LMFC = Left Motor Field Current
G1FC = Generator One Field Current
G2FC = Generator Two Field Current

$$\text{Bandwidth} = \frac{(\text{max value} - \text{min value})}{\text{average}}$$

$$\text{Chebyshev Deviation} = \frac{(\text{Summation}(\text{abs}(\text{Value} - \text{average})))}{\text{average}}$$

$$\text{Standard Deviation} = \frac{((\text{Summation}((\text{Value} - \text{average})^2))/n - 1)^{0.5}}{\text{average}}$$

(Summation = the summation from i = 1 to n where i = index)
(abs = absolute value)
(n = # of data points)

As a temporary measure, the code was modified so that the INITIAL routine would accept the signals with the wider bandwidths.

F. DIFFICULTIES WITH FAST SAMPLING RATE

One of the major problems which arose during stationary tests was the difficulties caused by the fast sampling time of the A/D converters in the SC-1. The A/D converters use a sample and hold technique with a 5 micro-second sampling time; the 5 micro-second voltage sample is converted to a digital word and sent to the SC-1 computer. The digital information is in the SC-1 memory within 25 micro-seconds of the start of the process. It seems that this fast sampling time causes the converters to read transient signals picked up by the motor field current and the generator field current transducers and that these transient signals are then

interpreted by the computer as being out of an acceptable range when in actuality a longer time average of the transducer signals is within range. The transients probably arise due to the pulse width modulation (pwm) method used to control the field currents in the motors and generators.

Difficulties were also had reading the left and right motor armature current transducer signals and the bus current transducer signal. The ANABOX software was modified so that the signals from these transducers are time averaged and thus smoothed out. This helps to eliminate the brief transient values picked up by the fast sampling A/D converter.

G. SC-1 BUBBLE MEMORY DIFFICULTIES

During the ANABOX software modification stage, the bubble memory in the SC-1 computer appeared to stop working; it failed to retain the information in the memory after the computer power was switched off. This problem was discussed with SwRI who indicated that the bubble memory modules are not as reliable as desired; they are prone to failures. SwRI suggested that the bubble memory be replaced with a compatible, more reliable electrically erasable programmable read-only-memory (EEPROM) module.

Later tests indicated that one channel of the bubble was bad. Programs of various sizes were loaded into the memory, and those programs significantly larger than 64k were garbled when the SC-1 power was switched on and off. This seemed to indicate that the bubble memory capacity had been reduced by half from 128k to 64k. This problem was worked around by keeping the size of the ANABOX software (when compiled and linked) near 64k.

Upon further discussions of the memory problems, SwRI indicated that the problem could be caused by the way in which the programs are being loaded into the bubble memory, and not with the memory circuits themselves.

H. GEARSHIFT ENCODER DIFFICULTIES

Problems were experienced with the gearshift encoder mechanism. Apparently, the mechanism had been damaged such that it was sending erroneous bit patters to the control computer. As a temporary solution until a new encoder was received, the OPERATE software routine (which is called by ANABOX and the main control program) was modified so as to accept input from a rotary switch.

I. DC GENERATOR VOLTAGE REGULATOR ISOLATION

One fault encountered concerned the voltage regulator for the dc generator. The chassis of the regulator serves as the regulator ground. This chassis was conducting to the vehicle chassis. This problem was discovered and corrected during the visit by SwRI personnel (Mr. Gary Stecklein and Mr. Ben Treichel) from September 28 through October 3, 1989.

J. COMPUTER A/D AND D/A CARDS

One of the A/D cards (card J13) in the SwRI computer did not operate properly. It was discovered that the input resistors to this card were missing. The card was returned to SwRI and the software was modified so that other channels could handle the data processed by the J13 card.

During the SwRI visit in late September 1989, J13 was tested by SwRI and reinstalled into the vehicle. It was soon discovered that output signals for the J15 and J16 D/A cards were only at half their expected value. A bad connection was discovered in the SC-1 internal 5 V power circuit. This 5 V circuit consists of four terminal posts connected in parallel powered by the SC-1 dc/dc converter. One of these posts which supplies the motherboard had not been connected properly. It was concluded that because the motherboard did not get enough power, the addition of the J13 caused excessive loading and thus the control signals from J15 and J16 were reduced. When this connection was resoldered, the control signals returned to normal.

Another problem soon appeared. The control signals to the motor field current began fluctuating excessively. The J13 card was removed and the fluctuations disappeared. It appeared that the J13 card was not operating properly and was somehow interfering with other portions of the SC-1.

K. ANABOX CONTROL PROGRAM INTEGRATION AND MODIFICATIONS

This section details efforts to debug and improve the ANABOX software routine. The ANABOX routine is a software simulation of the analog circuit controller. After the INITIAL routine was sufficiently debugged, debugging began on the ANABOX routine. The debugging of this routine helped to eliminate and correct many small problems in the vehicle hardware and in the control system. The debugging of ANABOX was a very important step in the effort in that it allowed work on the main control program to begin with most of the bugs eliminated from the vehicle hardware and control circuits.

As with the INITIAL routine, code was added to the ANABOX routine so that desired data is stored on the MILTOPE tape during tests. ANABOX, as delivered from SwRI, did not include data taking features. Some of the data desired included:

- Right and left motor field currents
- Right and left alternator field currents
- Right and left motor armature currents
- Right and left motor speeds
- Right and left sprocket speeds
- Final drive brake and clutch pressures

1. Modification to Print MILTOPE Data

During these tests, it became apparent that it was important to be able to obtain printouts of the data gathered by the MILTOPE recorder. It turned out that the data written by the MILTOPE module to the hard disk could not be printed by the data reduction program developed by David Taylor Research Center (DTRC). BRDEC wrote a separate program to print out the MILTOPE data.

2. Brake and Motor Equations Adjustments

It was discovered that the equations controlling the brakes in the INITIAL routine did not match the actual behavior of the brakes. The control voltage vs. brake pressure data was observed and graphed. The old equations were updated to reflect actual brake behavior.

During tests of the braking pedal, it was discovered that full displacement on the pedal was only bringing the brake pressure down to 100 psi and not 0 psi as it should have. It was determined that the pressure release switch on the brake pedal base was preventing full travel on the brake pedal. This meant that the signal from the brake pedal was only going from 5 V down to 2 V and not down to 0 V as it should have. To correct this, the brake pressure equation in the software was modified so that 2 V produced 0 psi (maximum braking).

The equations governing the dc motors also required adjustment. During INITIAL tests, the motors operated at around 1,400 r/min whereas the program was expecting to see speeds around 1,200 r/min. The INITIAL motor speed range values were adjusted to 1,200 - 1,600 r/min so that the test would be passed.

After work on ANABOX was started, BRDEC was able to perform the first preliminary field tests. These tests demonstrated that the vehicle could be driven with ANABOX, but with poor performance. More effort was needed to get ANABOX and all of the vehicle systems working properly in preparation for loading the main control program.

3. Regenerative Steering Modifications

Early field tests revealed that the mechanical brakes were coming on during turns in high speed. To correct this, the regenerative steering current differential between the inside and outside tracks was increased from ± 35 A to ± 50 A through modifications in the software.

4. Motor Armature Current and Bus Current Signal Fluctuation

During tests, it was found that there was excessive variation and fluctuation on the signal from the left and right motor armature current transducers and the bus current transducers. One possible solution was the installation of a passive filter circuit for the motor armature signal between the transducer and the input to the A/D board. One complication of this was that the output of the filter also went to the armature current meter on the engineer's station (the meter and the transducer are in parallel) which has a low impedance. The low impedance meter in parallel with the high impedance A/D board attenuated the filter output signal. Tests of the filter showed that it did not adequately reduce the fluctuations. Other solutions were sought.

Another solution was to modify the software so that it smoothed out the data from the armature and bus current A/D board. This solution was determined to be more effective. Code was added so that a running average of the data from the A/D board was calculated. The code worked by acquiring some number of data points from the A/D board (5-10 data points) and taking their average. Then the code would drop the oldest data point and acquire a new one. Thus each new average used data that had one new data point. This average would then be the value used by the computer and data taking system. This code was added to the inner loop portion of the software.

It was important to smooth out the armature and bus current data as much as possible because many of the control algorithms in the main control program use these values, and if they fluctuate excessively, the vehicle might operate in an unsteady or unstable fashion.

5. Addition of Spin Turn Feature

In order to improve the mobility of the vehicle, it was decide to add a spin turn capability to ANABOX. A spin turn is where the vehicle turns about its central axis. A new gearshift position (NEUTRAL-2 or N2) was added. When the shifter is placed in this position, a spin turn is possible. The spin turn is accomplished by changing the direction of the motor field current on one side.

6. Addition of Pivot Turn Feature

The software was modified to allow the vehicle to perform a pivot turn, which is when the vehicle turns with one track stationary. A pivot turn is done when the steering wheel is turned either hard left or hard right.

7. Revised Pivot Turn Feature

The pivot turn and low speed steering routines in ANABOX were revised to fix an armature contactor hardware problem. In the old low speed steering routine, the inner motor armature contactor was being opened while there was high inner motor armature circuit. This was damaging the contactor. The revised routine does not open the inner motor armature contactor until the inner motor armature current is less than 100 A. To accomplish this, the generator field current is set to 0 A until the contactor is open.

8. Motor Field Current Equations

Code was added to ANABOX, making the motor field current proportional to motor speed when the accelerator pedal is pushed beyond a certain displacement. This code makes the dc motors behave as a series wound motor. A series wound motor has the desirable property of providing high torque at low speeds. This displacement corresponds to about 0.25 V out of the full 0 to 5 V range. When the vehicle is stopped and the pedal is depressed beyond 0.25 V, full field current is activated according to the following equation:

$$FC = \frac{165 - 0.065 * (\text{RMOTOR Speed} + \text{LMOTOR Speed})}{2}$$

Thus, at zero speed, full field current is produced which gives the desired full torque. This equation holds until (RMOTOR Speed - LMOTOR Speed) / 2 is less than 1,000 r/min. When this is more than 1,000 r/min, the following equation is used:

$$FC = 100 - 0.0151 * (((\text{RMOTOR Speed} + \text{LMOTOR Speed}) / 2) - 1,000)$$

A graph of this equation is presented in Figure C-3.

The graph indicates that between 0 and 1,000 r/min, the field current will decrease at a rate of 0.065 A per r/min. Between 1,000 and 5,400 r/min, the field current will decrease at a rate of 0.0151 A per r/min.

FIELD CURRENT (amps)

$$FC = 165 - 0.065 (RMS + LMS)/2$$

−0.065 amp/(r/min)

Breakpoint (1,000 r/min)

$$FC = 165 - 0.0151 (RMS + LMS)/2$$

−0.0151 amp/(r/min)

(RMS + LMS)/2 (R/MIN*1,000)

—•— FIELD CURRENT
RMS = RIGHT MOTOR SPEED
LMS = LEFT MOTOR SPEED
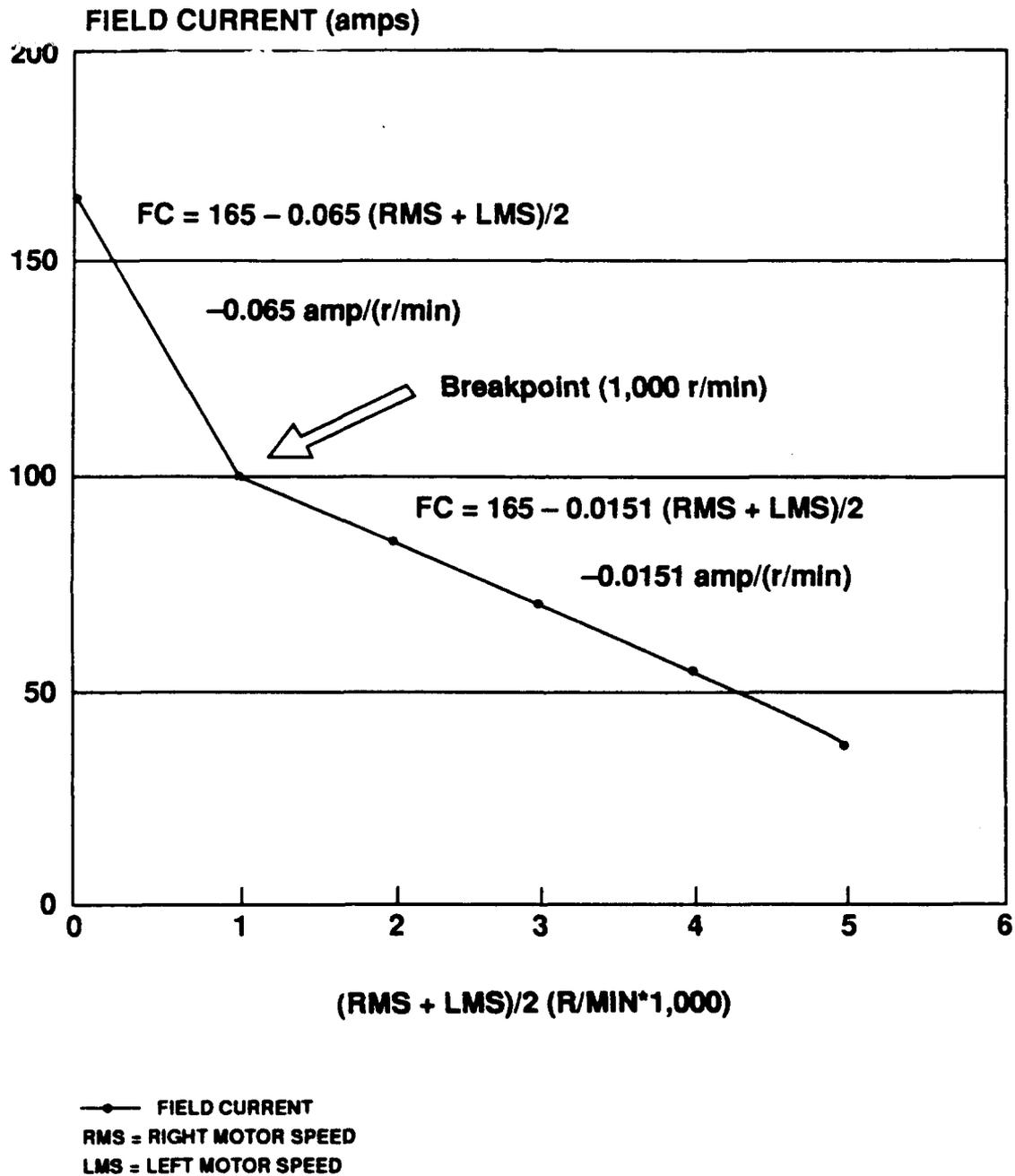
Figure C-3. Field I vs Speed (for dc motors)

9. Electric Brake Debugging

The electric braking routine was also added to the ANABOX software. When first field tested, the electric brakes did not appear to be providing the expected stopping power. Upon reviewing the ANABOX code, it was decided that an explicit statement would be added which makes the alternator field current 0 when the electric brakes are in operation. This assures that the only power on the dc bus during operation comes from the dc motors. This modification improves the stopping power of the electric brakes.

10. Limit of Engine Speed

During the preliminary field tests using ANABOX, the engine governor was set so that the engine speed would not rise above about 2,400 r/min. This was done to limit the power generated, and thus the top speed of the vehicle. At higher speeds, the FMC final drive units are very inefficient, and excessive heat could be generated in them causing damage. The ANABOX routine does not have all of the safety and warning software to permit full speed operation of the final drives. Other systems in the vehicle were also not yet fully developed and limiting engine power improved safety.

11. Problems with the J15 D/A Card

Test showed that the channel on the J15 D/A card which provided the control signal to the right motor field current controller began to output excessive noise. The J13 A/D card was not the problem because it was out of the circuit at the time.

L. ANABOX CONTROL PROGRAM STATUS

This program is now working satisfactorily and will provide good backup control of the vehicle when the main control program is not in use.

M. CONTROL ROUTINE DEBUGGING

After getting the ANABOX software operating reasonably well, the next step was beginning the task of debugging the main control routine. This routine is in many ways the "heart" of the electric drive demonstration project in that many of the goals of the project (such as enhanced vehicle mobility and fuel efficiency) are dependent upon proper operation of the main control routine. Due to initial lack of adequate documentation, it was initially difficult to begin understanding and debugging the control routine. The contract with SwRI was modified so that SwRI could support the project as it was completed. After the contract modification was awarded, SwRI sent updated documentation which allowed the analysis and modification of the main control routine to begin.

The debugging and integrating of the main control routine began in early November 1989. This routine contained many errors of syntax, spelling, and logic which had to be corrected. Some of these problems were minor, and others were quite serious. This section details some of the major problems encountered and their solutions.

1. Interrupt Timing Modification

It appeared that the timing on the interrupt scheme was causing problems. When the interrupt scheme on the 30 ms INNER loop and the 120 ms OUTER loop was removed and replaced with a 4 to 1 ratio, the gearshift would work properly and apparently all of the OUTER loop would run. When the 30ms/120ms timing interrupt was used, the OUTER loop apparently wasn't executing.

The INNER loop was originally set to begin executing every 30 ms. In theory, INNER should run at less than 30 ms so that time is left over for the OUTER loop to execute before the interrupt starts INNER again.

Tests showed that the INNER loop was running at about 40 ms instead of the expected 30 ms. Thus, the OUTER loop was never getting a chance to execute; this was causing the problems with the gearshift because the code to read the gearshift position is in the OUTER loop.

In comparison, the INNER in ANABOX executes in about 18 ms which leaves ample time (12 ms) for OUTER to execute.

As a preliminary test, the interrupt timing for INNER was adjusted from 30 ms to 60 ms. When tested, the OUTER loop then ran at about 18 ms while the INNER loop took about 32 ms to execute (instead of 40). The reason for the change in the execution time of INNER was unclear. The total execution time became 32 + 18 = 50 ms. Thus, with a 60 ms interrupt timing, both INNER and OUTER now had ample time to execute. The next step was to optimize the interrupt so as to minimize "slack time" when neither INNER nor OUTER was executing.

2. Modifications to the Shifting Code

During tests, it was observed that the gearshift codes to the computer were getting out of sequence. The problem was that the requested gear (RGEAR) was never equated to a validated gear (VGEAR) except when the present gear (PGEAR) and RGEAR were equal. It was observed that PGEAR and RGEAR are rarely equal. This was causing the gearshift codes to get out of sequence. The code was modified to correct this.

3. Modification of the Engine Start Routine

Problems were observed when the starter was released and the engine was started before the program got back to the conditional statement concerning engine cranking. The program was expecting to see the engine in the cranking mode but it had already started. This problem occurred when the engine was warm and started quickly. The code was modified to eliminate this problem.

4. Engine Speed and Horsepower Equations

Equation (a) (see page C-13) relates the optimal engine efficiency in terms of required horsepower to an engine speed. Equation (a) is used to drive engine speed in response to the power required for vehicle propulsion and auxiliary systems. Equation (b) (see page C-13) is

the same curve shifted in the direction of 15% less horsepower. Equation (b) is used to obtain present engine power from present engine speed; it is shifted by 15% so that not all the engine power is consumed by the vehicle propulsion and auxiliary systems. BRDEC found that in the program, Equation (b) was not the inverse of Equation (a) shifted by 15%. This was finally corrected by SwRI.

The problem described above was also causing the brakes to come on at odd times. Because Equations (a) and (b) were not causing the engine to deliver sufficient power to drive the motors at the desired speed, the brakes would come on to slow the motors down and thus prevent the engine from bogging down. Once Equations (a) and (b) were corrected, this problem disappeared.

$$DESRPM = f(DESHP) \qquad \text{Equation (a)}$$
$$TAEP = f(ENGRPM) \qquad \text{Equation (b)}$$

(DESRPM = desired engine r/min)
(DESHP = desired engine horsepower)
(TAEP = total available engine power)
(ENGRPM = engine r/min)

5. Other Program Corrections and Field Testing

BRDEC got the second MILTOPE working with the control program. The problem of printing to the recorder appeared to be the result of using bad tapes. Before, the data was randomly recorded. Also, there was a problem getting the MILTOPE program to process the data. It was found that this problem was dependent on the requested variables and sometimes certain variables could not be processed. For some reason, the program did not process DESLMC, DESRMC, and DAV at one time but processed all others; an error message "ILLEGAL FUNCTION CALL IN MODULE MILTOPE AT ADDRESS 0A87:0B6E" for those three variables was received. That problem was gone in successive testing afterward. A new tape was tried but no data was received using that tape.

It was discovered that some variables hadn't been declared and/or initialized. ODAMS wasn't included in any of the common blocks. ACCELM wasn't declared in COMMON.FOR and wasn't initialized in DATA.FOR. Therefore, ODAMS and ACCELM were the wrong values. (They could be anything). Since the desired inner and outer motor speed are f(ODAMS), their values were way off. Consequently, the desired inner and outer motor horsepower were wrong because desired horsepower is torque times desired speed. This contributed to the observed instability in engine speed because desired engine speed is f(desired motor hp + auxiliary).

$$ODAMS = \text{Old desired average motor speed} = f(ACCELM)$$

$$ACCELM = \text{Modified acceleration} = Accel * Brake$$

Earlier, it was observed that the logic of the conversion equations for all control system feedback signals was not quite right. It was difficult to fix because it was not known how the input values are registered in the computer A/D CARDS, especially negative values. The

ADTEST software was used to figure out how the micro integer values vary with analog input signals. They have a linear relationship with +5 V dc corresponding to a micro integer value (MIV) of 0000, 0 V dc corresponding to an MIV of 2047, and -5 V dc corresponding to an MIV of 4095. This newly obtained knowledge was used to rewrite all of the conversion equations of the vehicle feedback signals. Both positive and negative numbers are now seen on the MILTOPE for all bi-directional variables: dc bus currents, armature currents, and motor field currents. It is important that these feedback signals are converted correctly because they are used in calculations of torque, power, and electric braking condition. This contributed to the instability previously experienced with the control software.

The motor KPHI (FLUX) equation was modified to prevent KPHI from going negative when the vehicle is in Reverse and the field current is negative; otherwise, the motor torques would be negative in Reverse, which is not good. This fix, in turn, prevents the MAXAMS variable from going negative in Reverse direction.

The desired brake pressure equations were modified to give the correct operating range. Before, 250 psi was equal to a MIV of 78125; now, 250 psi is equal to a MIV of 65445, which is more accurate.

The DIMDR and DOMDR (desired inner and outer motor deceleration rate) equations were modified to give more reasonable values. The new equations reflect the deceleration rate per 5 sec with the unit of deceleration rate as rev/second squared. These equations are used in the electric braking section.

The TRNRAD (turn radius) equation (function of steer) was modified to prevent division by a 0 when steer is equal to 1 (steer = 1 = steering wheel in Neutral position).

The logic in the armature thermal limiting equation was modified so that the minimum value of armature current is limited at -800 A. The logic for maximum inner armature current was also modified to limit the maximum armature current to +800 A.

A new control program hex module was created incorporating the above changes. The hydraulic braking, electric braking, and counter rotation sections in this improved control module are still bypassed.

The braking grid resistance has not been implemented in the control program.

The control program was field tested on March 8, 1990. The vehicle was driven for about 10 minutes in forward and reverse direction. The vehicle performed much better than before; it was much smoother; the engine speed did not jump around excessively. Most of the instability seen earlier was eliminated by changes in the program. However, it appeared that there was some hesitation in engine speed as the accelerator was depressed. It was also observed that the main dc bus voltage remained fairly constant (about 100 V) and both motor field currents also remained fairly constant at about 165 to 170 A.

The data recorded on March 8, 1990, indicated that there were large instantaneous changes in DCAMPS (dc bus current). This, in turn, caused the motor armature currents to change instantaneously. This then caused the motor torques to change instantaneously creating an unstable condition in the system. As the motor torques go from a very small to a large value the DESRPM increased accordingly and it decreased accordingly in the other direction.

Because the change was so abrupt, the engine speed could not catch up with the DESRPM. This explained the hesitation felt in engine speed during field testing.

From analyzing the data, the villain appeared to be the DESACG (desired ac generator field current). DESACG values were changing rapidly, causing the changes mentioned above. Reviewing the DESACG equations indicated problems; the DESACG equations were a function of DCVOLT and DCAMPS (feedback signals), not DAV (desired armature voltage). DESACG should be a function of DAV. Furthermore, the DCVOLT and DAV values did not follow each other.

A new set of equations was implemented to correct the DESACG VALUES. The new equations are piecewise linear approximations based on the two ac generator load saturation curves. They are directly related to the DAV.

The following changes were implemented in the control program:

- Put in new DESACG equations.

- Made minor changes to INNER, OUTER, INITIAL, and OPERATE for the purpose of improving them.

- Edited the program to buffer the variables DAV and ACCEL using running average routines. This prevented large instantaneous changes in these variables.

- Made the variable DAV a direct function of ACCELM. Before, DAV was = f(doms) = f(dams) = f(accelm).

Two sets of Darlington power transistors failed during the March 8, 1990, field testing. Unfortunately, these were the last of these transistors which BRDEC had on hand, thus it was impossible to test the changes which buffered the DESACG, DAV, and ACCEL variables to prevent excessive fluctuations.

Initially, there was lots of instability in the operation of the vehicle. Many variables were oscillating (armature currents and voltages, DESACG, DAV, etc). Software changes have been made to control these oscillations, but haven't been tested on the vehicle yet.

Problems to be addressed:

- What is causing transistors to fail?
- How can oscillations and instability be better controlled?
- Are the computer D/A and A/D cards functional?

6. Present Status

The control program still needs more debugging. The oscillations in the control system need to be better understood and controlled. The motor field currents controllers and the D/A and A/D cards also need debugging.

Appendix D

Modified ANABOX Software

```
*********************************************************************
       SUBROUTINE ANABOX
*********************************************************************
C
$       INCLUDE (COMMON.FOR)
C       ====
C       DECLARE A LOGICAL CONSTANT FOR MODIFIED LOW SPEED TURN ROUTINE.11/13/89
        LOGICAL*1 TURNOFF
        SAVE TURNOFF
C         MOTOR FIELD CURRENT
C
C         IF(BRAKE.LT.0.95) ACCEL=0.0
C         FC =-0.01215* ACCEL + 130.61
C         IF(ACCEL.GT.5400.0) FC = 65.0
C         IF(ACCEL.LT.50.0) FC = 0.0
C         IF(STEER.LT.0.0) STEER=0.0
C
C
C         THE ELECTRIC BRAKES DON'T WORK REAL WELL AND RELAY 11 ENGAGES AT
C         THE WRONG TIMES CAUSING THE POWER SYSTEM TO DIM SO IT'S BEING
C         COMMENTED OUT FOR A WHILE. 8/9/89
C
C         PUT ELECTRIC BRAKES BACK IN. 10/26/89
        IF(BRAKE.LT.0.95)THEN
                ACCEL = 0.0
C       DISCONNECT ELECTRICAL POWER SOURCE TO MOTORS
                DESACG =0.0
        IDSACG =0.0
                OFFSET = #0900H
                CALL WWRITE(SEGMNT,OFFSET,IDSACG)
                IF (BITTST(.NOT.DIGOUT(1),11))THEN
                        CALL BITSET (DIGOUT(1),11)
                        OFFSET=#060AH
                        CALL WWRITE(SEGMNT,OFFSET,(.NOT.DIGOUT(1)))
                ENDIF
                FC=-1000.0*BRAKE+950.0
                IF(FC.GT.160.0)FC=160.0
        ELSE
                IF(BITTST(DIGOUT(1),11))THEN
                        CALL BITOFF (DIGOUT(1),11)
                        OFFSET=#060AH
                        CALL WWRITE(SEGMNT,OFFSET,(.NOT.DIGOUT(1)))
                ENDIF
C       FC=-0.01215*ACCEL+130.61
C
C
C         AN EQUATION TO MAKE FIELD CURRENT PROPORTIONAL TO MOTOR
C         SPEED, WHICH IT SORT OF IS ANYWAY. ANOTHER APPROACH WOULD BE TO
C         MAKE FIELD CURRENT PROPORTIONAL TO ARMATURE CURRENT, BUT WE DON'T
C         HAVE USEABLE VALUES OF ARMATURE CURRENT.  GJS-5/26/89
C         ADDED BY CAM FOR NOT IN ELECTRIC BRAKING MODE
                DESACG = .00075*ACCEL-0.03738
                IF (ACCEL.LT.50.0) DESACG=0.0
                IF(((RMOTOR+LMOTOR)/2.0).LE.500.0)THEN
                        FC = 165.0 - 0.065*((RMOTOR+LMOTOR)/2.0)
                ELSE
C
C         COMMENTED OUT BECAUSE I THINK THIS IS CAUSING OSCILLATION IN THE
C         STEERING 8/1/89. 8/9/89-- IT WAS! USING THE EQUATION ABOVE ALLOWS
C         SPINS AND PIVOTS AT LOW SPEEDS AND BEN'S EQUATION ALLOWS THE
C         VEHICLE TO WORK FAIRLY WELL AT HIGHER SPEEDS.
```

```
C          FC=100.0-0.01591*(((RMOTOR+LMOTOR)/2.0)-1000.0)
C
C          BEN'S ORIGINAL EQUATION
C                     FC=-0.01215*ACCEL+130.61
                ENDIF
                IF(ACCEL.GT.5400)FC=65.0
C               IF(ACCEL.LT.50)FC=0.0
                IF(ACCEL.LT.100)FC=0.0
                IF(STEER.LT.0.0)STEER=0.0
C          THIS "ENDIF" BELONGS WITH THE REST OF THE ELEC BRAKE ROUTINE
           ENDIF
C
C
C          SFC=-35.0*STEER+35.0
C          NEW EQUATION TO TRY TO GET MORE DYNAMIC STEERING.
C          TRIED 50 AMPS FIRST AND IT STEERED A LOT BETTER.
C          NOW LETS TRY 75A. 4/17/89
C
           SFC=-75.0*STEER+75.0
C
C          LIKEWISE THIS ONE
C          IF(SFC.GT.35.0) SFC = 35.0
C
           IF(SFC.GT.75.0) SFC = 75.0
           IF(TRNDIR.EQ.-1) THEN
                DESLMC = FC + SFC
                DESRMC = FC - SFC
           ELSE
                DESRMC = FC+SFC
                DESLMC = FC-SFC
           ENDIF
C
           IF(DESRMC.LT.0.0) DESRMC=0.0
           IF(DESLMC.LT.0.0) DESLMC=0.0
C
           IDSRMC=INT((-.0159+.0293*DESRMC)*819.0)
C
C
C          STATMENT BELOW ADDED BY SULLIVAN 12/22/88 BECAUSE
C          NEGATIVE NUMBERS DON'T WORK
C
C
C
           IF(IDSRMC.LT.0) IDSRMC=0
           OFFSET=#0902H
           CALL WWRITE(SEGMNT,OFFSET,IDSRMC)
           IDSLMC=INT((-.035+.028*DESLMC)*819.0)
C          SEE COMMENT ABOVE ABOUT IDSRMC
C
           IF(IDSLMC.LT.0) IDSLMC=0
           OFFSET=#0A02H
           CALL WWRITE(SEGMNT,OFFSET,IDSLMC)
C
C
C          BRAKES
C
           BRKPSI = 250.0 * BRAKE
           IF(BRKPSI.GT.250.0) BRKPSI = 250.0
           IF(BRKPSI.LT.0.0) BRKPSI = 0.0
           IF(STEER.LT.0.0) STEER=0.0
```

```
        SBPSI = -250.0 * STEER + 250.0
        IF(TRNDIR.EQ.-1) THEN
                LBRAKE = BRKPSI - SBPSI
                RBRAKE = BRKPSI
        ELSE
                LBRAKE = BRKPSI
                RBRAKE  = BRKPSI-SBPSI
        ENDIF
C
        IF(LBRAKE.LT.0.0) LBRAKE=0.0
        IF(RBRAKE.LT.0.0) RBRAKE=0.0
C       IF(ACCEL.LT.5.0) THEN
C               LBRAKE=0.0
C               RBRAKE=0.0
C       ENDIF
C
C       THE EQUATION FOR THE BRAKE HAS BEEN CHANGE EMPIRICALLY
C       TO IMPROVE FUNCTIONING. GJS 1/18/89
C
C       ORIGINAL EQUATION
C
        ILBRKE=INT4(LBRAKE/.00382)
C
C
C       EQUATION DEREIVED FROM FINAL DRIVE TESTS AND DATA IN FINAL REPORT
C
C       ILBRKE=INT4(LBRAKE/.0061)
        OFFSET=#0B0CH
        CALL WWRITE(SEGMNT,OFFSET,ILBRKE)
C
C
C       SIMILARLY FOR THE RIGHT BRAKE
C
C
        IRBRKE=INT4(RBRAKE/.00382)
C
C       RIGHT BRAKE EQUATION - FROM TEST DATA AND FINAL REPORT
C
C       IRBRKE=INT4(RBRAKE/.0061)
        OFFSET=#0B0EH
        CALL WWRITE(SEGMNT,OFFSET,IRBRKE)
C
C
C       ENGINE
C
C       DESRPM EQUATION BELOW CHANGED TO FACILITATE SHOP TESTING.
C       ENGINE EITHER IDLES OR GOES LIKITY SPLIT.1/5/89
C
C
C
C       DESRPM = 0.2701 * ACCEL + 1886.0
C
C
C
        DESRPM = ACCEL/3 + 1000.0
C
C
C
        IF(DESRPM.LT.700.0) DESRPM = 700.0
```

```
                    IF(ACCEL.LT.50.0) DESRPM=700.0
                    IF(DESRPM.GT.2800.0) DESRPM = 2800.0
C
C
C                   THE BELOW EQUATION CHANGED BECAUSE THE D/A BOARD
C                   DOSEN'T SEEM TO HANDLE A ZERO VALUE WHEN DESRPM=700
C                   1/5/89
C
C                   DIDN'T HELP MUCH. PROBLEM STILL EXISTS.1/23/89
C
C                   IDSRPM=INT((DESRPM-700.0)/.501534)
C
C
C
C
C
C                   IDSRPM = INT((DESRPM-690)/.501534)
C
C
C
C
C
C
                    IF(IDSRPM.GT.4094) IDSRPM=4094
                    OFFSET=#0A00H
                    CALL WWRITE(SEGMNT,OFFSET,IDSRPM)
C
C
                    M2=IDSRPM
                    M28=DESRPM
C
C
C                   GENERATOR FIELD CURRENT
C
C
C
C
C
C                   MXGNFC CHANGED FROM 4 TO 5.0 BECAUSE 4 ISN'T
C                   HIGH ENOUGH.--- G.J. SULLIVAN 12/22/88
C
C
C
C
C
C
                    MXGNFC = 5.0
                    MXARMC = MAX(LMACUR,RMACUR)
                    IF(MXARMC.GT.300.0) MXGNFC = MXARMC *(-0.02)+ 10.0
C                   ADD TO SET IDSACG TO 0 FOR SLOW SPEED STEERING
                    IF(TURNOFF) THEN
                            IDSACG=0.0
                    ELSE
                            DESACG =.00075* ACCEL - 0.03738
                            IF(ACCEL.LT.50.0) DESACG = 0.0
                            IF(DESACG.GT.MXGNFC) DESACG = MXGNFC
C
C
C                   THE EQUATION USED DOES NOT GIVE THE FULL 4096
C                   VALUE SINCE (FROM ABOVE) THE MAX VALUE OF ACCEL IS GOING TO BE
C                   ABOUT 6500 AND DESACG WILL BE ABOUT 4.8. THEN IDSACG WILL BE ABOUT
C                   2458 WHICH IS ONLY 2458/4096X5.0 OR 3V. THAT  IS TO SAY THAT 511.875
C                   SHOULD BE ABOUT 1000. GJS--12/23/88
```

```fortran
C
C       ALSO SEE OPRATE FOR ACCEL VALUE
C
C
                DESACG=0.248+0.725*DESACG-0.02*DESACG**2+0.00288*DESACG**3
C
C       *2 ADDED TO IDSACG EQUATION BELOW TO FACILITATE TESTING 1/5/89
C
C       IDSACG=INT(DESACG*511.875)
C
C
C
                IDSACG=INT(DESACG*1023.75)
        ENDIF
C
C
        OFFSET=#0900H
        CALL WWRITE(SEGMNT,OFFSET,IDSACG)
C
C       THESE ROUTINES ADDED TO TURN OFF THE ARMATURE CURRENT
C       ON THE INSIDE TRACK DURING LOW SPEED TURNS. THAT
C       MOTOR BECOMES A SHORT CICUIT AT VERY LOW SPEEDS
C       GJS 1/6/89
C
C       ALSO ADDED ROUTINES TO CHECK IF THE INSIDE TRACK MOTOR ARMATURE
C       CURRENT IS LESS THAN 100 A BEFORE DISCONNECTING THE INSIDE
C       ARMATURE CONTACTOR.   CAM 11/6/89
        IF((ISTEER .GT. 1524).AND.(RSPRKT.LT.30.0))THEN
                IF (.NOT.BITTST(DIGOUT(1),5)) GOTO 30
                TURNOFF=.TRUE.
                IF (I.GE.1)THEN
                        IF (RMACUR.LT.100.0) THEN
                                CALL BITOFF(DIGOUT(1),5)
                                TURNOFF=.FALSE.
                                GOTO 20
                        ENDIF
                ENDIF
                I=I+1
        ELSE
                I=0
        ENDIF
        IF (BITTST(DIGOUT(1),5)) GOTO 30
        IF ((PGEAR.EQ.P).OR.(PGEAR.EQ.N)) GOTO 30
        CALL BITSET(DIGOUT(1),5)
20      OFFSET=#060AH
        CALL WWRITE(SEGMNT,OFFSET,(.NOT.DIGOUT(1)))
30      CONTINUE
C
C
C
C
C
        IF((ISTEER .LT. 524).AND.(LSPRKT.LT.30.0))THEN
                IF(.NOT.BITTST(DIGOUT(1),6))GOTO 31
                TURNOFF=.TRUE.
                IF (I.GT.1) THEN
                        IF (LMACUR.LT.100.0) THEN
                                CALL BITOFF(DIGOUT(1),6)
                                TURNOFF=.FALSE.
                                GOTO 21
```

```
                              ENDIF
                   ENDIF
                   I=I+1
          ELSE
                   I=0
          ENDIF
          IF (BITTST(DIGOUT(1),6)) GOTO 31
          IF ((PGEAR.EQ.P).OR.(PGEAR.EQ.N)) GOTO 31
          CALL BITSET(DIGOUT(1),6)
21        OFFSET=#060AH
          CALL WWRITE(SEGMNT,OFFSET,(.NOT.DIGOUT(`)))
31        CONTINUE
C
C**********************************************************************************
C**********************************************************************************
C**     INPUTS BELOW HAVE BEEN ADDED TO GET DATA ON FIELDS OF GENERATORS
C**     AND MOTORS FOR MILTOPE. GJS-1/31/89
C**********************************************************************************
C**********************************************************************************
C
C
C
C
C         READ RIGHT MOTOR FIELD CURRENT
C
C
C
C
          OFFSET=#0202H
          CALL MREAD(SEGMNT,OFFSET,IRMFCR)
          CALL WWRITE(SEGMNT,OFFSET,IRMFCR)
41        CALL MREAD(SEGMNT,OFFSET,IRMFCR)
          IF (BITTST(IRMFCR,16)) GOTO 41
C         THE MULTIPLIER 1.02 CORRECTS THE ERROR IN THE TRANSDUCER
C
C         CONVERT RIGHT MOTOR FIELD
C
C**********************************************************************************
C**********************************************************************************
C*     The values for IRMFCR and ILMFCR are accepted for the range 0-1600 *
C*     for positive values and 2048 to 3700 for negative values to stop   *
C*     extraneous values from the A/D board showing up on the miltope.     *
C*     This will allow current values from -202A to 195A. Values above     *
C*     170A are not possible unless the circuit fails. These equations     *
C*     do not yield negative values on the miltope. GJS, 2/13/89           *
C**********************************************************************************
C**********************************************************************************
C
C
          IRMFCR=((.NOT.IRMFCR).AND.#07FFH)
                                            IF (IRMFCR.LE.1600) THEN
                   RMFCUR=FLOAT(IRMFCR)*0.122*1.02
          ELSE
                   IF((IRMFCR.GE.2048).AND.(IRMFCR.LT.3700)) THEN
                           RMFCUR=FLOAT(IRMFCR-2048)*0.122*1.02
                   ELSE
                           RMFCUR=0.0
                   END IF
          END IF
C
```

```
C          READ LEFT MOTOR FIELD CURRENT
C
C
C
           OFFSET=#0506H
           CALL MREAD(SEGMNT,OFFSET,ILMFCR)
           CALL WWRITE(SEGMNT,OFFSET,ILMFCR)
51         CALL MREAD(SEGMNT,OFFSET,ILMFCR)
           IF (BITTST(ILMFCR,16)) GOTO 51
C
C          THE MULTIPLIER 1.02 CORRECTS THE ERROR IN THE TRANSDUCER
C
C
C          CONVERT LEFT MOTOR FIELD CURRENT
C
C
C
           ILMFCR=((.NOT.ILMFCR).AND.#07FFH)
                                                IF (ILMFCR.LE.1600) THEN
                   LMFCUR=FLOAT(ILMFCR)*0.122*1.02
           ELSE
                   IF((ILMFCR.GE.2048).AND.(ILMFCR.LT.3600)) THEN
                           LMFCUR=FLOAT(ILMFCR-2048)*0.122*1.02
                   ELSE
                           LMFCUR=0.0
                   END IF
           END IF
C
C
C          READ G1 GEN FIELD CURRENT
C
C
C
           OFFSET=#0300H
           CALL MREAD(SEGMNT,OFFSET,IG1FCR)
           CALL WWRITE(SEGMNT,OFFSET,IG1FCR)
61         CALL MREAD(SEGMNT,OFFSET,IG1FCR)
           IF (BITTST(IG1FCR,16)) GOTO 61
           G1FCUR=FLOAT((.NOT.IG1FCR).AND.#07FFH)*0.00244
C
C
C
C          READ G2 GEN FIELD CURRENT
C
C
C
           OFFSET=#010EH
           CALL MREAD(SEGMNT,OFFSET,IG2FCR)
           CALL WWRITE(SEGMNT,OFFSET,IG2FCR)
71         CALL MREAD(SEGMNT,OFFSET,IG2FCR)
           IF (BITTST(IG2FCR,16)) GOTO 71
           G2FCUR=FLOAT((.NOT.IG2FCR).AND.#07FFH)*0.00244
C
C
C
C          READ DC BUS CURRENT
C
C
C
C
```

```
                OFFSET = #0106H
                CALL MREAD(SEGMNT,OFFSET,IDAMPS)
                CALL WWRITE(SEGMNT,OFFSET,IDAMPS)
81              CALL MREAD(SEGMNT,OFFSET,IDAMPS)
                IF (BITTST(IDAMPS,16)) GOTO 81
C               CALL CURB(IDAMPS)
C
C
C               CONVERT DC BUS CURRENT
C
C
                IF(((.NOT.IDAMPS).AND.#07FFH).LE.2047) THEN
                        DCAMPS = FLOAT((.NOT.IDAMPS).AND.#07FFH)*1.0
                ELSE
                        IF((IDAMPS.GE.2048).AND.(IDAMPS.LE.4095)) THEN
                                DCAMPS = (FLOAT(IDAMPS-2048))*1.0
                        ELSE
                                DCAMPS = 1600.0
                        END IF
                END IF
C
C
C
C               READ DC BUS VOLTS
C
C
C
C
                OFFSET = #0104H
                CALL MREAD(SEGMNT,OFFSET,IDCVLT)
                CALL WWRITE(SEGMNT,OFFSET,IDCVLT)
91              CALL MREAD(SEGMNT,OFFSET,IDCVLT)
                IF (BITTST(IDCVLT,16)) GOTO 91
C
C
C
C               CONVERT DC BUS VOLTS
C
C
                IF(((.NOT.IDCVLT).AND.#07FFH).LE.2047) THEN
                        DCVOLT = FLOAT((.NOT.IDCVLT).AND.#07FFH)*0.147
                ELSE
                        IF((IDCVLT.GE.2048).AND.(IDCVLT.LE.4095)) THEN
                                DCVOLT = (FLOAT(IDCVLT-2048))*0.147
                        ELSE
                                DCVOLT = 280.0
                        END IF
                END IF
C
C
C               READ LEFT MOTOR ARMATURE VOLTAGE
C
C
                OFFSET = #0508H
                CALL MREAD(SEGMNT,OFFSET,ILMAVT)
                CALL WWRITE(SEGMNT,OFFSET,ILMAVT)
70              CALL MREAD(SEGMNT,OFFSET,ILMAVT)
                IF (BITTST(ILMAVT,16)) GOTO 70
C
C               CONVERT LEFT MOTOR ARMATURE VOLTAGE
```

```
C
            IF(((.NOT.ILMAVT).AND.#07FFH).LE.2047) THEN
                    LMAVLT = FLOAT((.NOT.ILMAVT).AND.#07FFH)*0.147
            ELSE
                    IF ((ILMAVT.GE.2048).AND.(ILMAVT.LE.4095)) THEN
                            LMAVLT = (FLOAT(ILMAVT-2048))*0.147
                    ELSE
                            LMAVLT = 280.0
                    END IF
            END IF
C
C       READ RIGHT MOTOR ARMATURE VOLTAGE
C
            OFFSET = #0204H
            CALL MREAD(SEGMNT,OFFSET,IRMAVT)
            CALL WWRITE(SEGMNT,OFFSET,IRMAVT)
80          CALL MREAD(SEGMNT,OFFSET,IRMAVT)
            IF (BITTST(IRMAVT,16)) GOTO 80
C
C       CONVERT RIGHT MOTOR ARMATURE VOLTAGE
C
            IF (((.NOT.IRMAVT).AND.#07FFH).LE.2047) THEN
                    RMAVLT = FLOAT((.NOT.IRMAVT).AND.#07FFH)*0.147
            ELSE
                    IF ((IRMAVT.GE.2048).AND.(IRMAVT.LE.4095)) THEN
                            RMAVLT = (FLOAT(IRMAVT-2048))*0.147
                    ELSE
                            RMAVLT = 280.0
                    END IF
            END IF
C
C
C       READ LEFT MOTOR ARMATURE CURRENT
C
C
C
C
            OFFSET = #0504H
            CALL MREAD(SEGMNT,OFFSET,ILMAC)
            CALL WWRITE(SEGMNT,OFFSET,ILMAC)
101         CALL MREAD(SEGMNT,OFFSET,ILMAC)
            IF (BITTST(ILMAC,16)) GOTO 101
            CALL CURLM(ILMAC)
C
C
C       CONVERT LEFT MOTOR ARMATURE CURRENT
C
C
C
C       IF(((.NOT.ILMAC).AND.#07FFH).LE.2047) THEN
C               LMACUR = FLOAT((.NOT.ILMAC).AND.#07FFH)*0.5
C       ELSE
C               IF((ILMAC.GE.2048).AND.(ILMAC.LE.4095)) THEN
C                       LMACUR = (FLOAT(ILMAC-2048))*0.5
C               ELSE
C                       LMACUR = 800.0
C               END IF
C       END IF
C
C
C
```

```
C
C
C
C        READ RIGHT MOTOR ARMATURE CURRENT
C
C
C
C
C
         OFFSET = #0200H
         CALL MREAD(SEGMNT,OFFSET,IRMAC)
         CALL WWRITE(SEGMNT,OFFSET,IRMAC)
111      CALL MREAD(SEGMNT,OFFSET,IRMAC)
         IF (BITTST(IRMAC,16)) GOTO 111
C
C
C        CONVERT RIGHT MOTOR ARMATURE CURRENT
C        IRMAC=(.NOT.IRMAC).AND.#07FFH
C        IF(IRMAC.LE.2047) THEN
C                RMACUR = FLOAT(IRMAC)*0.5
C        ELSE
C                IF((IRMAC.GE.2048).AND.(IRMAC.LE.4095)) THEN
C                RMACUR = (FLOAT(IRMAC-2048))*0.5
C                ELSE
C                    RMACUR = 800.0
C                END IF
C        END IF
         CALL CUR(IRMAC)
C
C
C        READ RIGHT BRAKE PRESSURE
C
C
         OFFSET = #0100H
         CALL MREAD(SEGMNT,OFFSET,IPRBRK)
         CALL WWRITE(SEGMNT,OFFSET,IPRBRK)
121      CALL MREAD(SEGMNT,OFFSET,IPRBRK)
         IF(BITTST(IPRBRK,16)) GOTO 121
C
C
C
C        CONVERT RIGHT BRAKE PRESSURE
C
C
C
         PRBRK = FLOAT(.NOT.(IPRBRK).AND.#07FFH)*0.1467
C
C
C
C        READ LEFT BRAKE PRESSURE
C
C
         OFFSET = #0102H
         CALL MREAD(SEGMNT,OFFSET,IPLBRK)
         CALL WWRITE(SEGMNT,OFFSET,IPLBRK)
131      CALL MREAD(SEGMNT,OFFSET,IPLBRK)
         IF(BITTST(IPLBRK,16)) GOTO 131
C
C
C        CONVERT LEFT BRAKE
```

```
C           PLBRK = FLOAT(.NOT.(IPLBRK).AND.#07FFH)*0.1467
C
C
C
C
C
C

          RETURN
          END
```

```
*************************************************************************
        SUBROUTINE INTIAL
*************************************************************************
C
$          INCLUDE (COMMON.FOR)
C          ====
           EXTERNAL INNER
           INTEGER IC
           CALL INIT
           DO 10 IC=1,8
                    DIGOUT(IC)=0
10         CONTINUE
C
C          GOTO 25
C
20         CALL GFTEST
C
C
C
C
           CALL ESTART
C
           IF(GFCHK) THEN
                    GFCHK=.FALSE.
                    GOTO 20
           ENDIF
C
C          CALL MOTEST
C
C          CALL BRKTST
C
           CALL DELAY(1000)
C          DECODE GEAR SHIFT
25         INTL = .TRUE.
           DO 30 IC = 1,6
                    CALL OPRATE
                    CALL DELAY(120)
30         CONTINUE
           INTL = .FALSE.
C          TEST FOR PARK
           IF(VDGEAR.NE.P) THEN
C                   SET NOT IN PARK ERROR
                    CALL BITSET(DIGOUT(6),7)
                    m50=m50+1
C                   CALL MLTOPE
                    DIGOUT(6)=0
                    GOTO 25
           ENDIF
C
C          THE THREE CURRENTS ADDED BY SULLIVAN 12/19/88 SINCE THE
C          FIELDS WERE COMING ON.
C
C
C
C
           IDSRMC=0
           IDSLMC=0
           IDSACG=0
C
C
```

```
C           WRITE(IDSRMC)
            OFFSET=#0902H
            CALL WWRITE(SEGMNT,OFFSET,IDSRMC)
C
C           WRITE(IDSLMC)
C
            OFFSET=#0A02H
            CALL WWRITE(SEGMNT,OFFSET,IDSLMC)
C
C           WRITE(IDSACG)
C
            OFFSET=#0900H
            CALL WWRITE(SEGMNT,OFFSET,IDSACG)
C
C           CALL DELAY(1000)
C
C
            RGEAR=VDGEAR
            PGEAR=N
            CALL NUTRAL
            CALL BITOFF(DIGOUT(2),6)
            CALL BITSET(DIGOUT(2),5)
C           WRITE(DIGOUT(2))
            OFFSET = #070AH
            CALL WWRITE(SEGMNT,OFFSET,(.NOT.DIGOUT(2)))
C
C
C
            m38=digout(1)
            m39=digout(2)
            m40=digout(3)
            m41=digout(4)
            m42=digout(5)
            m43=digout(6)
            m44=digout(7)
            m45=digout(8)
            CALL MLTOPE
            DO 40 IC=3,8
                    DIGOUT(IC)=0
40          CONTINUE
            CALL DELAY(125)
            CALL SETINT(128,INNER)
            CALL START
            CALL OUTER
            END
```

```
          $INTERRUPT
**************************************************, ***********.********************
          SUBROUTINE INNER
** * * * *****************************..*********************************** * * * * ***
C
$         INCLUDE (COMMON.FOR)
C         ====
          CHARACTER*94 STATE
          CALL SAV87(STATE)
          M2=M2+1
          CALL MTOPE
C
C
C         ANALOG=TRUE ADDED BY SULLIVAN 12/20/88
C
C
C
          ANALOG=.TRUE.
          INTL=.FALSE.
C         IF(ANALOG) THEN
C
C
C         CALL OPRATE ADDED BY SULLIVAN 12/20/88
C
C
C
          CALL OPRATE
          CALL ANABOX
C         TO TEST SC1 WITH OPERATING, CALL ADTEST INSTEAD OF ANABOX
C         ELSE
C           CALL CONTRL
C         ENDIF
          IF(IMCNT.GE.4) THEN
            M1=RMOTOR
                    M4=LMOTOR
                    M5=LSPRKT
                    M6=RSPRKT
                    M7=ENGRPM
                    M8=PRBRK
                    M9=PLBRK
                    M13=DCVOLT
                    M14=DCAMPS
                    M15=ACCEL
                    M16=STEER
                    M17=RMACUR
                    M18=LMACUR
                    M21=G1FCUR
                    M22=G2FCUR
                    M23=RMFCUR
                    M24=LMFCUR
                    M25=DESRMC
                    M26=DESACG
                    M27=DESLMC
                    M28=DESRPM
                    M31=TCRSCV
                    M32=TCLSCC
                    M33=TGEN1S
                    M34=TGEN2S
                    M38=IT2104
                    M19=IT2369
```

```
                    M40=ITDSCV
                    M41=ITENGC
                    M42=ITGBSV
                    M43=ITNOIL
                    M44=ITNEXH
                    M45=ITNAIR
                    CALL MLTOPE
                    DO 10 I=3,8
                    DIGOUT(I)=0
10                  CONTINUE
                    IMCNT=0
            ENDIF
            IMCNT=IMCNT+1
C
            INTL=.TRUE.
            CALL RST87(STATE)
            RETURN
            END
```

```
**********************************************************************
      SUBROUTINE OUTER
**********************************************************************
C
$     INCLUDE (COMMON.FOR)
      ANALOG=.TRUE.
10    IF(IMCNT.GT.1) GOTO 10
C
      M50=M50+1
      CALL OPRATE
C     ALL FUNCTIONS EXCEPT SYNCRO MOTOR/SPROCKET
C
      IF(VDGEAR.EQ.A) VDGEAR=PGEAR
      IF((RGEAR.EQ.PGEAR).AND.(.NOT.UPSHFT).AND.(.NOT.DNSHFT))
     -RGEAR=VDGEAR
      IF(PDSTAT.GT.2) RGEAR=PGEAR
      IF(RGEAR.NE.PGEAR) THEN
                IF(PGEAR.EQ.P)  CALL PARK
                IF(PGEAR.EQ.N)  CALL NUTRAL
                IF(PGEAR.EQ.R)  CALL REVRSE
                IF(PGEAR.EQ.D1) CALL DRIVE1
                IF(PGEAR.EQ.D2) CALL DRIVE2
      ENDIF
C
C     BELOW IS A ROUTINE FOR A SPIN TURN USING THE SWITCH INSTEAD OF
C     THE GEAR SHIFT. SEE ALSO PROGRAM "OPRATE" WHERE VALUES OF PLACE
C     WERE DIDDLED WITH TO MAKE THIS ROUTINE WORK. GJS. 5/16/89
C
C
C
C
      PLACE=SBITS(DIGIN(2),8,1)
                                  IF(PGEAR.EQ.N)THEN
          IF((PLACE.EQ.220).OR.(PLACE.EQ.240))THEN
C               IF ((PLACE.EQ.128).OR.((PLACE.GE.146).AND.(PLACE.LE.151)))THEN
                        CALL BITSET(DIGOUT(1),5)
                CALL BITSET(DIGOUT(1),6)
                CALL BITSET(DIGOUT(1),13)
                CALL BITSET(DIGOUT(1),14)
C               IF(PLACE.EQ.128)THEN
                IF (PLACE.EQ.240)THEN
                        CALL BITOFF(DIGOUT(1),8)
                        CALL BITOFF(DIGOUT(1),9)
                        CALL BITSET(DIGOUT(1),7)
                        CALL BITSET(DIGOUT(1),10)
                ENDIF
C               IF((PLACE.GE.146).AND.(PLACE.LE.151))THEN
                IF(PLACE.EQ.220)THEN
                        CALL BITOFF(DIGOUT(1),7)
                        CALL BITOFF(DIGOUT(1),10)
                        CALL BITSET(DIGOUT(1),8)
                        CALL BITSET(DIGOUT(1),9)
                ENDIF
          ELSE
          CALL BITOFF(DIGOUT(1),5)
          CALL BITOFF(DIGOUT(1),6)
          CALL BITOFF(DIGOUT(1),7)
          CALL BITOFF(DIGOUT(1),8)
          CALL BITOFF(DIGOUT(1),9)
          CALL BITOFF(DIGOUT(1),10)
```

```
                    CALL BITOFF(DIGOUT(1),13)
                    CALL BITOFF(DIGOUT(1),14)
            ENDIF
            OFFSET=#60AH
            CALL WWRITE(SEGMNT,OFFSET,(.NOT.DIGOUT(1)))
        ENDIF
C
C
C
C       SYNCRO MOTOR/SPROCKET
C
        IF((UPSHFT).OR.(DNSHFT)) CALL SHIFT
C
        CALL ECAN
C
C
        CALL TEMPER
C
C
C       M1=RMOTOR
C       M4=LMOTOR
C       M7=ENGRPM
C       M16=STEER
C       M23=RMFCUR
C       M24=LMFCUR
C       M25=DESRMC
C       M27=DESLMC
C       M28=DESRPM
C       M31=TCRSCV
C       M32=TCLSCC
C       M33=TGEN1S
C       M34=TGEN2S
C          M38=IT2104
C          M39=IT2369
C          M40=ITDSCV
C          M41=ITENGC
C          M42=ITGBSV
C          M43=ITNOIL
C          M44=ITNEXH
C          M45=ITNAIR
C       CALL MLTOPE
C
C
20      IF(IMCNT.LE.1)   GOTO 20
        GOTO 10
C
        END
```

```
****************************************************************************
      SUBROUTINE OPRATE
****************************************************************************
C
$     INCLUDE (COMMON.FOR)
C     ====
C
      IF(INTL) GOTO 40
C     READ ACCELERATOR PEDAL INPUT
C
      OFFSET = #0108H
      CALL MREAD(SEGMNT,OFFSET,IACCEL)
      CALL WWRITE(SEGMNT,OFFSET,IACCEL)
10    CALL MREAD(SEGMNT,OFFSET,IACCEL)
      IF (BITTST(IACCEL,16)) GOTO 10
      M11=IACCEL
      IACCEL=((.NOT.IACCEL).AND.#07FFH)
C
C     CONVERT ACCELERATOR PEDAL
C
      OACCEL=ACCEL
      ACCEL = 3.857*FLOAT(IACCEL)-1265.14
      IF(ACCEL.GT.5400.0) ACCEL=5400.0
      IF(ACCEL.LT.0.0) ACCEL=0.0
      IF(REVDIR) ACCEL=0.0
C
C
C        IACCEL LIMIT CHANGED FROM 1960 TO 2200 AND AC-1 ADJUSTED
C        TO 4.9V BECAUSE IT IS UNDESIRABLE TO GO FROM FULL SPEED AND
C        POWER TO NOTHING SO QUICKLY. --G.J.SULLIVAN 12/23/88
C
C
C
C
C
C
C
      IF((IACCEL.GT.2200).OR.(IACCEL.LT.100)) THEN
              ACCEL=0.0
              CALL BITSET(DIGOUT(5),14)
      ENDIF
C     READ BRAKE PEDAL
      OFFSET = #010AH
      CALL MREAD(SEGMNT,OFFSET,IBRAKE)
      CALL WWRITE(SEGMNT,OFFSET,IBRAKE)
20    CALL MREAD(SEGMNT,OFFSET,IBRAKE)
      IF (BITTST(IBRAKE,16)) GOTO 20
      IBRAKE=((.NOT.IBRAKE).AND.#07FFH)
C     CONVERT BRAKE PEDAL
C
C
C
C        THE BRAKE PEDAL DOES NOT HAVE FULL TRAVEL AND AS A RESULT
C        THE EQUATION BELOW DOES NOT WORK RIGHT. THE TRAVEL IS OBSTRUCTED
C        BY THE EMERGENCY RELIEF VALVE FOR THE BRAKES AND THE VOLTAGE
C        RANGE FOR INPUT BC-1 GOES FROM 2-5VOLTS.
C
C
C
C     BRAKE = .0007413*FLOAT(IBRAKE)-.2341
C
```

```
C
C       NEW EQUATION
C
C
        BRAKE = .0008137*FLOAT(IBRAKE)-.6604
C
C
C
C
        IF(BRAKE.GT.1.0) BRAKE=1.0
        IF(BRAKE.LT.0.0) BRAKE=0.0
        IF((IBRAKE.GT.1960).OR.(IBRAKE.LT.100)) THEN
           BRAKE=1.0
                   CALL BITSET(DIGOUT(5),13)
        ENDIF
C       READ STEERING INPUT
        OFFSET = #010CH
        CALL MREAD(SEGMNT,OFFSET,ISTEER)
        CALL WWRITE(SEGMNT,OFFSET,ISTEER)
30      CALL MREAD(SEGMNT,OFFSET,ISTEER)
        IF (BITTST(ISTEER,16)) GOTO 30
        ISTEER=((.NOT.ISTEER).AND.#07FFH)
C
C       CONVERT STEERING AND DETERMINE TURN DIRECTION
C
        IF(ISTEER.GE.1024) THEN
           TRNDIR=1
                   STEER=-0.001212*FLOAT(ISTEER)+2.2788
C          TURN TO THE RIGHT
        ELSE
           TRNDIR=-1
                   STEER=0.001212*FLOAT(ISTEER)-0.20606
        ENDIF
C
        IF(STEER.GT.1.0) STEER=1.0
        IF((STEER.LT.0.0).AND.STEER.GT.-0.0337)) STEER=0.0
        IF((STEER.LE.-0.0337).AND.(STEER.GE.-0.069)) STEER=-1.0
        IF(STEER.LT.-0.069) CALL BITSET(DIGOUT(5),12)
C
C       READ ACTUAL ENGINE SPEED
C
        OFFSET = #0D04H
        CALL MREAD(SEGMNT,OFFSET,IENRPM)
        ENGRPM = FLOAT(IENRPM)*4.762
        IF(ABS(TUNE10-ENGRPM).GT.300.0) THEN
           IF(ENGRPM.GT.TUNE10) THEN
                   ENGRPM = TUNE10+300.0
                   ELSE
                   ENGRPM = TUNE10-300.0
                   ENDIF
        ENDIF
        TUNE10 = ENGRPM
C
C       CHECK FOR ENGINE MAG PICKUP FAILURE (DEFAULT TO 600 RPM)
C
C          READ DIGIN(1)
        OFFSET = #0608H
        CALL MREAD(SEGMNT,OFFSET,DIGIN(1))
        M12=DIGIN(1)
        P1P7 = (.NOT.SBITS(DIGIN(1),7,1))
```

```
             IF((ENGRPM.EQ.0.0).AND.(P1P7.GT.0)) THEN
               CALL BITSET(DIGOUT(6),4)
                      ENGRPM = 700.0
             ENDIF
C
C       READ ACTUAL MOTOR AND ACTUAL SPROCKET SPEEDS
C
C       READ RMOTORE SPEED
        OFFSET = #0C00H
        CALL MREAD(SEGMNT,OFFSET,IRMTOR)
        RMOTOR=FLOAT(IRMTOR)*41.25
C
C
C
C       READ LMOTOR SPEED
        OFFSET = #0D00H
        CALL MREAD(SEGMNT,OFFSET,ILMTOR)
        LMOTOR=FLOAT(ILMTOR)*41.25
C       READ RSPRKT SPEED
        OFFSET = #0C02H
        CALL MREAD(SEGMNT,OFFSET,IRSPKT)
        RSPRKT=FLOAT(IRSPKT)*1.974
C
C
C         READ LSPRKT SPEED
        OFFSET = #0D02H
        CALL MREAD(SEGMNT,OFFSET,ILSPKT)
        LSPRKT=FLOAT(ILSPKT)*1.974
C
C       CHECK FOR MAG PICKUP FAILURE ON THE MOTORS AND SPROCKETS
C
        IF((PGEAR.NE.P).AND.(PGEAR.NE.N)) THEN
          IF((.NOT.(UPSHFT)).OR.(.NOT.(DNSHFT))) THEN
               IF(ABS(RMOTOR-RSPRKT*FDR).GT.200.0) THEN
                      IF((RMOTOR-RSPRKT*FDR).LT.0.0) THEN
                             CALL BITSET(DIGOUT(6),14)
                             RMOTOR = RSPRKT*FDR
                      ELSE
                             CALL BITSET(DIGOUT(6),2)
                             RSPRKT = RMOTOR/FDR
                      ENDIF
               ENDIF
               IF(ABS(LMOTOR-LSPRKT*FDR).GT.200.0) THEN
                      IF((LMOTOR-LSPRKT*FDR).LT.0.0) THEN
                             CALL BITSET(DIGOUT(6),1)
                             LMOTOR = LSPRKT*FDR
                      ELSE
                             CALL BITSET(DIGOUT(6),3)
                             LSPRKT = LMOTOR/FDR
                      ENDIF
               ENDIF
          ENDIF
        ENDIF
C
C
C
40      ODGEAR = DGEAR
        DGEAR = 0
        OFFSET = #0708H
        CALL MREAD(SEGMNT,OFFSET,DIGIN(2))
```

```fortran
        PLACE = (SBITS(DIGIN(2),8,1))
C
C       THIS WAS ADDED BECAUSE THE TWO HIGH BITS WERE WIRED HIGH FOR THE GEAR
C       SHIFT EXPERIMENT 5/10/89
C
        IF(PLACE.EQ.192)PLACE=0
        IF (((PLACE.GE.196).AND.(PLACE.LE.199)).OR.((PLACE.GE.204).AND.
     -      (PLACE.LE.205))) DGEAR = P
        IF (((PLACE.GE.200).AND.(PLACE.LE.201)).OR.((PLACE.GE.216).AND.
     -      (PLACE.LE.217)).OR.(PLACE.EQ.219)) DGEAR = R
C
C       THE NUETRAL ROUTINE BELOW HAS BEEN COMMENTED OUT SO I COULD PUT IN
C       A ROUTINE THAT WOULD GIVE US A SPIN TURN
C
        IF ((((PLACE.EQ.210).OR.((PLACE.GE.212).AND.(PLACE.LE.215))).OR.(PLACE.EQ.
     -      .OR.((PLACE.GE.146).AND.(PLACE.LE.151)))DGEAR = N
C       THE BELOW ROUTINE MAKES A SPIN TURN WORK WITH THE SWITCH GEAR SHIFT
C
C
        IF ((PLACE.EQ.212).OR.(PLACE.EQ.240).OR.(PLACE.EQ.220)) DGEAR = N
C
C
C
        IF (((PLACE.GE.242).AND.(PLACE.LE.243)).OR.((PLACE.GE.246).AND.
     -      (PLACE.LE.247))) DGEAR = D1
        IF (((PLACE.GE.249).AND.(PLACE.LE.251)).OR.(PLACE.EQ.254))
     +      DGEAR = D2
        IF (((PLACE.GE.228).AND.(PLACE.LE.229)).OR.((PLACE.GE.236).AND.
     +      (PLACE.LE.239))) DGEAR = A
        IF (DGEAR.EQ.0) THEN
                I = I + 1
        ELSE
                I = 0
        ENDIF
C       VALIDATE GEAR
        IF((DGEAR.EQ.ODGEAR).AND.(DGEAR.NE.0)) THEN
          J=J+1
        ELSE
                J=0
        ENDIF
        IF(J.GT.3) VDGEAR=DGEAR
C       SET ERROR
        IF (I.GT.5) THEN
                VDGEAR = PGEAR
                IF ((VDGEAR.EQ.P).OR.(VDGEAR.EQ.N)) VDGEAR = D1
                CALL BITSET(DIGOUT(5),15)
        ENDIF
C       BELOW DATA TRANSMISSIONS COMMENTED OUT BY SULLIVAN
C       TO TRY TO HAVE THE DATA SENT FROM ONE PLACE IN
C       PROGRAM.  1/3/89
C
C
C       m10=place
C       m11=i
C       m12=j
C       m35=dgear
C       m36=odgear
C       m37=vdgear
C       m38=digout(1)
C       m39=digout(2)
```

```
C        m40=digout(3)
C        m41=digout(4)
C        m42=digout(5)
C        m43=digout(6)
C        m44=digout(7)
C        m45=digout(8)
C        call mltope
         RETURN
         END
```

Distribution for Report No. 2507

Department of Defense

1 Director, Technical Information
Defense Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

1 Director
Defense Nuclear Agency
ATTN: TITL
Washington, DC 20305

2 Defense Technical Information Center
Cameron Station
ATTN: DTIC-FDAC
Alexandria, VA 22304-6145

Department of the Army

1 HQDA (DAMA-AOA-M)
Washington, DC 20310

1 HQDA (DALO-TSM)
Washington, DC 20310

1 HQDA (DAEN-RDL)
Washington, DC 20314

1 HQDA (DAEN-MPE-T)
Washington, DC 20314

1 Commander
US Army Missile Research and
Development Command
ATTN: AMSMI-PR
Redstone Arsenal, AL 35809

1 Director
Army Materials and Mechanics Research
Command
ATTN: AMXMR-RL (Technical Library)
Watertown, MA 02172-0001

1 Commander
Chemical Research R&D Center
ATTN: SMCCR-SPS (Technical Library)
Aberdeen Proving Ground, MD 21005

1 Commander
US Army Aberdeen Proving Ground
ATTN: STEAP-MT-U (GE Branch)

1 Director
US Army Materiel System Analysis Agency
ATTN: AMXSY-MP
Aberdeen Proving Ground, MD 21005-5071

1 Director
US Ballistics Research Laboratory
ATTN: AMXBR-OD-ST (STINFO)
Aberdeen Proving Ground, MD 21005-5066

1 Director
US Army Engineer Waterways Experiment Station
ATTN: Chief, Library Branch
Technical Information Center
Vicksburg, MS 39180

1 Commander
US Army Armament Research and
Development Command
ATTN: SMCAR-TSS
Dover, NJ 07801-5001

1 Commander
US Army Troop Support and Aviation Materiel
Readiness Command
ATTN: DRSTS-MES (1)
4300 Goodfellow Blvd.
St. Louis, MO 63120

2 Director
Petrol and Fld Svc Dept
US Army Quartermaster School
Ft. Lee, VA 23801

1 US Army Tank Automotive Command
ATTN: DRSTA-TSL
Warren, MI 48090

  US Army Laboratory Command
1 ATTN: SLCMT-MN (M. Levy)
1 ATTN: SLCMT-MCZ (J. Wells)
Materials Technology Laboratory
Watertown, MA 02172-0001

2	US Army Tank Automotive Command Research, Development and Engineering Center Propulsion Systems Division ATTN: Mr. Gus Khalil (AMSTA-RG) Warren, MI 48090		1	US Army AMCCOM ATTN: Joseph Menke 1032 N. Thornwood Davenport, IA 52804

2 US Army Tank Automotive Command
Research, Development and Engineering Center
Propulsion Systems Division
ATTN: Mr. Gus Khalil (AMSTA-RG)
Warren, MI 48090

1 Commander
US Army Electronics Research and
   Development Command
ATTN: DELSD-L
Fort Monmouth, NJ 07703-5301

1 President
US Army Aviation Test Board
ATTN: STEBG-PO
Fort Rucker, AL 36360

1 US Army Aviation School Library
PO Drawer O
Fort Rucker, AL 36360

1 HQ, 193D Infantry Brigade (Panama)
ATTN: AFZU-FE
APO Miami 34004

2 Special Forces Detachment, Europe
ATTN: PBO
APO New York 09050

2 Engineer Representative
USA Research & Standardization Group (Europe)
Box 65
FPO 09510

1 Commander
Rock Island Arsenal
ATTN: SARRI-LPL
Rock Island, IL 61299-7300

1 HQDA
ODCSLOG
DALO-TSE
Room 1E588, Pentagon
Washington, DC 20310-0561

1 Plastics Technical Evaluation Center
ARRADCOM, Bldg. 3401
Dover, NJ 07801

1 Commandant
US Army Engineer School
ATZA-CDD
Fort Belvoir, VA 22060

1 US Army AMCCOM
ATTN: Joseph Menke
1032 N. Thornwood
Davenport, IA 52804

1 Commander
Headquarters, 39th Engineer Bn (Cbt)
For)evens, MA 01433

1 President
US Army Airborne, Communications, and
   Electronics
ATTN: STEBF-ABTD
Fort Bragg, NC 28307

1 President
US Army Armor and Engineer Board
ATTN: ATZK-AE-PD-E
Fort Knox, KY 40121-5470

1 Director
ATTN: STSTO-TPP
Tobyhanna Army Depot
Tobyhanna, PA 18466-5097

1 Commander and Director
USA FESA
ATTN: FESA-TS
Fort Belvoir, VA 22060

1 HQ, USAEUR & Seventh Army
Deputy Chief of Staff, Engineer
ATTN: AEAEN-MT-P
APO New York 09403

1 Director
US Army TRADOC
Systems Analysis Activity
ATTN: ATAA-SL (Technical Library)
White Sands Missile Range, NM 88002

Director
US Army LABCOM/Ballistic Research Lab
12 ATTN: SLCBR-IB-B
10 Charles Leveritt
1 Jody Wojciechowski
1 Madeline M. Decker
Aberdeen Proving Ground, MD 21005-5066

Belvoir RD&E Center

Circulate

1   Commander SATBE-Z
    Technical Director SATBE-ZT
    Assoc Tech Dir (E&A) SATBE-ZTE
    Assoc Tech Dir (R&D) SATBE-ZTR
    Admin Officer SATBE-ZA
    Operations Sergeant SATBE-ZM
    Dir., Resource Management SATBE-C
    Dir., Automated Services Dir SATBE-B
    Dir., Facilities and Support Dir SATBE-W
    Dir., Product Assurance & Engr Dir SATBE-T
    Dir., Combat Engineering Dir SATBE-J
    Dir., Logistics Equipment SATBE-F
    Foreign Intelligence Div SATBE-HF
2   SATBE-F
5   SATBE-FGE
3   Tech Reports Ofc ASQNK-BRS-G
3   Security Ofc SATBE-WS
2   Technical Library SATBE-BT
1   Public Affairs Ofc SATBE-I
1   Ofc of Chief Counsel SATBE-L

Department of the Navy

1   Director
    Physics Program (421)
    Office of Naval Research
    Arlington, VA 22217

2   Commander
    Naval Facilities Engineering Command
    ATTN: Code 032-B
          062
    200 Stoval Street
    Alexandria, VA 22332

1   US Naval Oceanographic Office
    Navy Library/NSTL Station Bay
    St. Louis, MO 39522

1   Library (Code L08A)
    Civil Engineering Laboratory
    Naval Construction Battalion Center
    Port Hueneme, CA 93043

1   Director
    Earth Physics Program
    Code 464
    Office of Naval Research
    Arlington, VA 22217

1   Naval Training Equipment Center
    ATTN: Technical Library
    Orlando, FL 32813

3   Naval Sea Systems Command
    ATTN: P. Schneider PMS377J1
    Washington, DC 20362

1   Naval Air Development Center
    ATTN: V. S. Agarwala, Code 6062
    Warminster, PA 18974

3   David W. Taylor Naval Reseach Center
    ATTN: A. G. S. Morton
          Code 2813
    Annapolis, MD 21402

2   David Taylor Research Center
    Marine Corps Program Office: Code 1240
    ATTN: Mr. Michael Gallagher
    Bethesda, MD 20084-5000

Department of the Air Force

1   HQ USAF/RDPT
    ATTN: Commander
    Washington, DC 20330

1   HQ USAF/PREEU
    Chief, Utilities Branch
    Washington, DC 20330

1   HQ Air Force Engineering & Services Center
    Technical Library FL7050
    Tyndall AFB, FL 32403

1   US Air Force
    Warner Robins Air Logistics Center
    WR-ALC/MMEM
    Warner-Robins AFB, GA 31098

1   Chief, Lubricants Branch
    Fuels and Lubrications Division
    ATTN: AFWAL/POSL
    Wright-Patterson AFB, OH 45433